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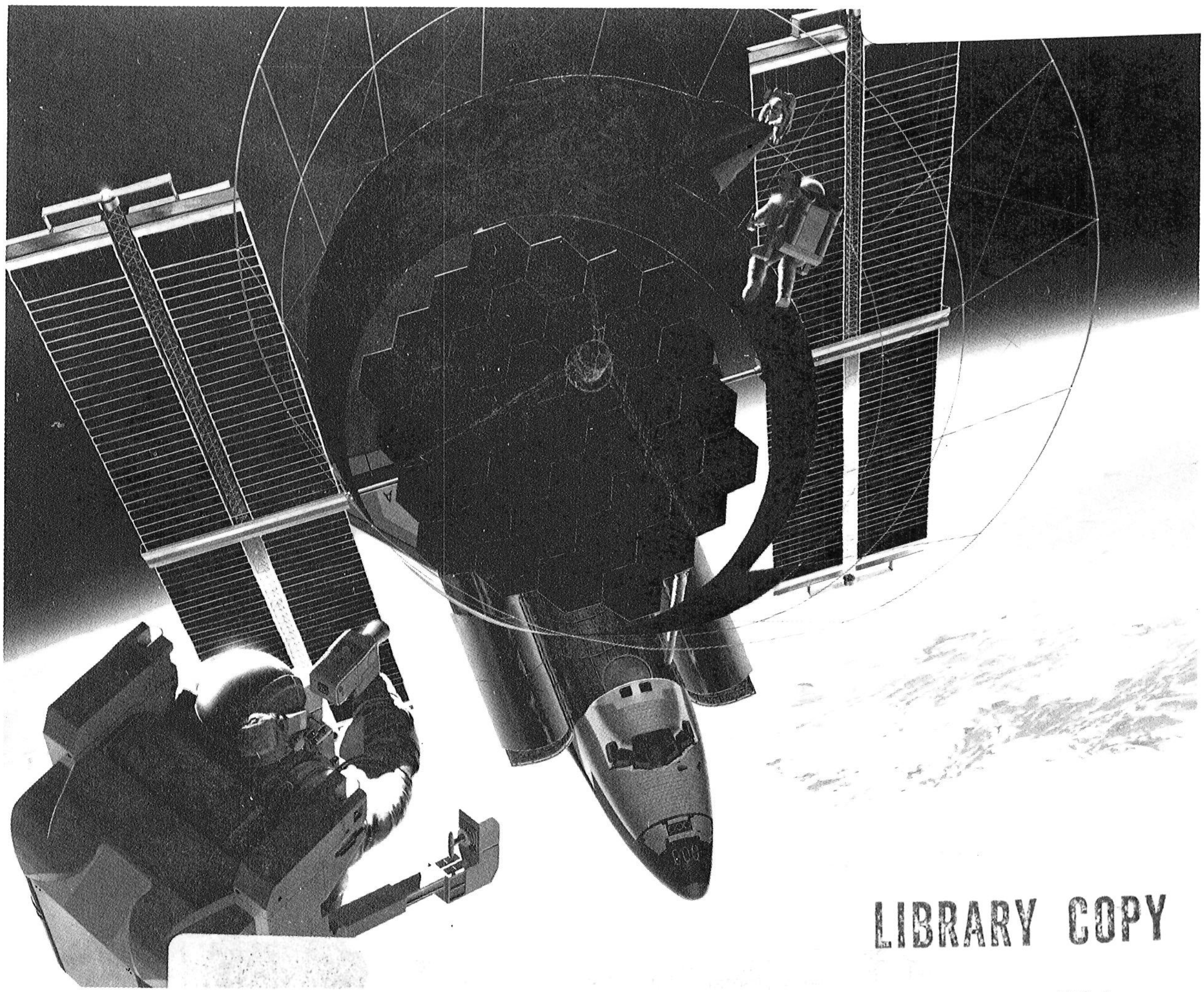
Large Deployable Reflector Science and Technology Workshop

Volume I - Executive Summary



June 1984

Asilomar Conference Center
Pacific Grove, California
June 21–25, 1982

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PREFACE

This report summarizes the scientific and technical results of the meeting held on June 21–25, 1982, at Asilomar, California, and sponsored by the National Aeronautics and Space Administration (NASA) to evaluate the prospects for astronomy and to evaluate the state of technology – for the Large Deployable Reflector (LDR). LDR is a submillimeter/far-infrared telescope which is projected to fly in space in the 1990s. The scientific rationale and technology requirements were defined and the systems considerations and a technology assessment was made for LDR at this same workshop.

This report is volume one of three volumes that record the proceedings of the NASA LDR Science and Technology Workshop. Volume two is the Scientific Rationale and Technology Requirements and volume three is the Systems Considerations and Technology Assessment.

The workshop was sponsored by the NASA Office of Aeronautics and Space Technology (OAST) and the Office of Space Science and Applications (OSSA). The material for this report was generated by scientists and engineers from private industry, universities, and government agencies.

The LDR Science and Technology Workshop and the report of its findings would not have been possible without the contribution of many people. A complete list of the workshop participants is shown in appendix A.

Special acknowledgements go to the LDR Science and Technology Workshop Chairman, W. J. Welch; to the Science Chairman, T. Phillips; to the Technology Chairman, K. Soosar; and to the panel chairmen:

E. Wright (Cosmology)
G. Wynn-Williams (Extragalactic and Galactic Structure)
S. Strom (Stellar Evolution)
N. Evans (Interstellar Medium)
A. Tokunaga (Solar System and Planetary Studies)
T. Pitts (Systems and Missions)
R. Angel (Optics)
M. Mikulas (Structures and Materials)
F. Tolivar (Sensing and Control)
C. McCreight (Scientific Instruments)

Paul Swanson, Jim Breckinridge, Tom Kuiper, and Bob Freeland deserve special mention for providing valuable input, criticism, and comments.

Finally, special thanks should be given to Mike Kiya, Dave Hollenbach, and Bill Gilbreath for their successful efforts in bringing the LDR workshop into being, and to Frank Fiore and Bruce Baumrucker of Vectors Unlimited for administrating the workshop .

C. A. Leidich
R. B. Pittman
NASA Ames Research Center
March 30, 1983

I. INTRODUCTION

A. GENERAL OVERVIEW

The Large Deployable Reflector (LDR) will be a 20-m-diam telescope designed for infrared (IR) and submillimeter (submm) astronomical measurements. The LDR will be used to study such diverse astronomical phenomena as stellar and galactic formation, cosmology, and planetary atmospheres. The technology to undertake such an ambitious project is not well in hand, but with sufficient augmentation of the generic technology development efforts currently under way, LDR will be ready in the mid-1990s. This volume will give a summary of the scientific rationale, the functional requirements, the technology assessment, and the future recommendations for LDR developed at this workshop.

Stars and solar systems begin their lives in the cold depths of optically opaque clouds of dust, atoms, and molecules. At far-IR, submm, and radio wavelengths, these clouds are transparent and the feeble radiation originating within them can be seen and properly studied only by telescopes of sufficiently great size and sensitivity. Only a fraction of the radiation from star-forming regions is emitted at radio wavelengths, and, therefore, large, ground-based radio telescopes have limited sensitivity to such sources. These regions radiate primarily in the submm and IR regions of the spectrum; thus, a large instrument such as LDR, operating in space at these wavelengths, is essential in order to observe the physical and chemical processes which are necessary precursors to the coalescence of this material into protostars. With LDR we will be able to witness the growth of Sun-like stars and perhaps to learn whether the formation of planetary systems is a common occurrence in the universe.

The Primordial Nebula from which our solar system formed was probably several times larger than its current size. The large size of the LDR primary mirror (diameter of ~20 m) will give it the angular resolution to resolve similar known or suspected star- and planet-forming regions within 500 light years of the Earth, including the known star-forming molecular cloud in Taurus. LDR will provide a wealth of new data on the early evolution of solar systems.

Current theories postulate that the universe was formed in a gigantic explosion, commonly called the "Big Bang," 15 billion years ago. The Cosmic Background Radiation (CBR) is the remnant of this explosion and is a probe into condition that existed prior to the formation of galaxies. The fluctuations in this background may yield some explanation of the present complex distribution of matter in the universe and of the formation of galaxies and clusters of galaxies. No fluctuations in this background have yet been detected, but LDR will be able to map fluctuations as small as one part in a million and with unprecedented spatial resolution. With this resolution we may be able to study clusters of galaxies to determine whether the galaxies formed first and then were drawn together into clusters or whether the clusters formed first and then the individual galaxies formed.

The reason these important observations have not been made previously is that radiation in the important IR and submm wavelength region is severely attenuated by the Earth's atmosphere. Far-IR and submm radiation carries information vital to the decoding of the structure of stars as they form and to the understanding of the coldest and most distant and highly red-shifted objects in the universe. The results from airplane and balloon-borne observations and, most recently, from the Infrared Astronomical Satellite (IRAS) show that there is an enormous amount of important information to be obtained from a sensitive, high-resolution telescope operating above the Earth's atmosphere at these wavelengths.

In attacking these challenging scientific problems, LDR will be a major component in NASA's long-term commitment to place in space permanent, orbiting astronomical observatories that are sensitive to

radiation over the full range of the electromagnetic spectrum. In 1986 NASA expects to place in orbit the Space Telescope (ST), the first large, permanent optical/ultraviolet orbiting observatory. The ST should provide the necessary observations to establish an accurate distance scale for the universe and to chart the evolutionary history of galaxies. Later, the Advanced X-Ray Astrophysics Facility (AXAF) will permit the panoply of high-energy phenomena in the universe to be studied. Between IRAS and LDR will come the Shuttle Infrared Telescope Facility (SIRTF). SIRTF will provide observations of the highest attainable sensitivity at wavelengths from 5 μm to 200 μm. It will extend IRAS's pioneering all-sky survey to fainter, more distant sources and carry out detailed studies of many of the problems to be attacked in a complementary fashion by LDR.

Among this complement of extraordinary observatories, LDR represents a significant departure in design and philosophy. LDR will be the first astronomical observatory to be erected and assembled in space, a distinction that brings with it major challenges to current technology. At the same time, achieving LDR objectives will provide invaluable experience in the art of constructing high-precision, large space structures.

Substantial technical developments are needed to complete the necessary technology base for LDR, but these are now considered achievable in the near-term. In particular, unique challenges lie ahead in the development of ultra-lightweight deployable mirrors, advanced mirror fabrication techniques, and advanced structures and structural controls for space applications. LDR is only one of the systems which will be possible as a result of these technological advances.

Just as important as the baseline technology issues are the system integration requirements. For example, the STS has constraints on packaging and weight that affect overall telescope size, stability, and control requirements.

Likewise, there will be an effect on testing requirements because of the ultra-lightweight and large size of LDR. Integrated ground testing prior to launch and deployment does not appear feasible. We must, therefore, pursue major improvements in our ability to model and simulate complex space systems with a high degree of confidence and to validate these models with individual technology demonstrations.

The LDR has the potential to be a major springboard for this new generation of space systems for scientific, commercial, and military applications. There is a large degree of confidence within the scientific and engineering community that a 20-m IR and submm telescope in space can be a reality within the next 10–15 years.

B. LDR HISTORY AND STATUS

The impetus for the development of the LDR began in the late 1970s with two parallel proposals – one for study of a large submm telescope by the Jet Propulsion Laboratory (JPL), and the other for study of a large IR telescope by the Ames Research Center (ARC). These proposed studies were united into one project intended to lead to the development of a large-aperture (at least 10-m effective diameter) telescope for far-IR and submm astronomy.

Discussions with university scientists and representatives of aerospace companies working on related problems indicated that such a telescope would be technically feasible in the 1990s; this conclusion was reinforced by technical studies sponsored by NASA. Even at this early stage in its definition, the LDR was among the projects reviewed by the Astronomy Survey Committee ("Field Committee") of the National Academy of Sciences. In 1981, this committee, which was charged with defining a program of astronomical

exploration and study extending well into the 1990s, recommended LDR with high priority as a major new NASA Space Program for development in the late 1980s, saying:

> The Astronomy Survey Committee recommends the construction of a Large Deployable Reflector of the 10 m class in space to carry out observations in the far-infrared and submillimeter regions of the spectrum that are inaccessible from the ground. A number of important scientific problems are uniquely accessible to such a Large Deployable Reflector in space. For distances less than 500 parsecs, the projected beam diameter will be less than 1000 AU.
>
> Direct measurements of the sizes of nearby clouds collapsing to become stars will thus be possible at far-infrared wavelengths, which can penetrate the surrounding clouds of dust that invariably obscure small-scale features at optical wavelengths. In addition, the wavelength regions accessible to an LDR contain spectral lines of atoms, ions, and molecules that reflect a wide range of astrophysical conditions.
>
> Studies of these features will yield otherwise unobtainable information about the structure and dynamics of planetary atmospheres; the heating, cooling, and chemical composition of the interstellar medium; and, because of the penetrating power of long-wavelength radiation, chemical abundances in the highly luminous, but optically obscured nuclei of active galaxies.
>
> The sensitivity and high angular resolution of an LDR will also make it possible to study newly forming stars in optically obscured regions of nearby external galaxies enhancing our understanding of galactic evolution and of the dynamical processes that stimulate star formation. Such an instrument can also probe the structure of the early Universe and the mechanisms of galaxy formation through studies of small-scale spatial fluctuations in the cosmic microwave background radiation.

Because of this strong scientific endorsement for LDR, NASA plans to begin hardware development in the Early 1990s, and initial operational capability by the mid-1990s. To meet the technical challenges necessary to begin development on an LDR, an intensive technology program is required prior to the start of the actual flight hardware development.

To this end, a joint NASA-ARC/JPL LDR study team was formed in 1979. Upon completing an extensive industry survey and an initial conceptual design study (won competitively by Lockheed) in 1979, the ARC/JPL study team drafted an LDR Technology Development Plan in 1981.

The most pressing technology area identified in this development plan was the method for fabricating lightweight mirror segments with a surface error of less than 2 μm in large quantities. A segment definition study was won by Perkin-Elmer (PE) for assessing segment technology and providing recommendations for segment development. This study was begun in 1981 and was completed in March 1983.

In addition to the Lockheed and PE contractual efforts, a multidiscipline science and technology consulting team has been formed with participants from both universities and industry. Also, support for LDR from NASA Langley Research Center (LaRC) in the areas of structures and structural analysis has been established.

Finally, a need-to-know with the Defense Advanced Research Projects Agency (DARPA) has been established, and an exchange of information and expertise between DARPA and NASA in the area of large deployable optical technology is continuing.

LDR will be a major national project with far-reaching astronomical and technical ramifications. The Asilomar workshop marked the first major attempt to define the scientific rationale for the LDR and to compare the astronomical requirements with the technical possibilities. The large number (>100) of scientists and technologists involved in the workshop and the wide range of topics discussed are evidence of the excitement and challenge of this project.

Volume III includes a current LDR Bibliography, including information written after this workshop. Other helpful information includes a glossary of terms relating to LDR (appendix B) in this volume and a list of abbreviations and acronyms (appendix C).

C. WORKSHOP PURPOSE AND ORGANIZATION

Study activity for LDR began in the late 1970s and by 1981 it was recognized by NASA that major interaction was required between the science and technology communities. The scientific community would define the scientific rationale for LDR as well as conceptually describe a potential instrument complement, and the technical experts would assess the technologies needed for the LDR and plan how to develop those capabilities that are currently beyond the state of the art.

Consequently, NASA sponsored the LDR Science and Technology Workshop at the Asilomar Conference Center, Pacific Grove, California, in June 1982. Over 100 scientists and engineers from universities, NASA centers, Department of Defense agencies, and private industry participated. The organization of the Workshop is shown in figure I-1. Appendix A contains a complete list of all workshop participants. The scientific panels were organized around the following topics: Cosmology, Extragalactic and Galactic Structure, Stellar Evolution, Interstellar Medium, and Solar System and Planetary Studies. The technical panels consisted of the following: Systems and Missions, Optics, Structures and Materials, Sensing and Control, and Science Instruments.

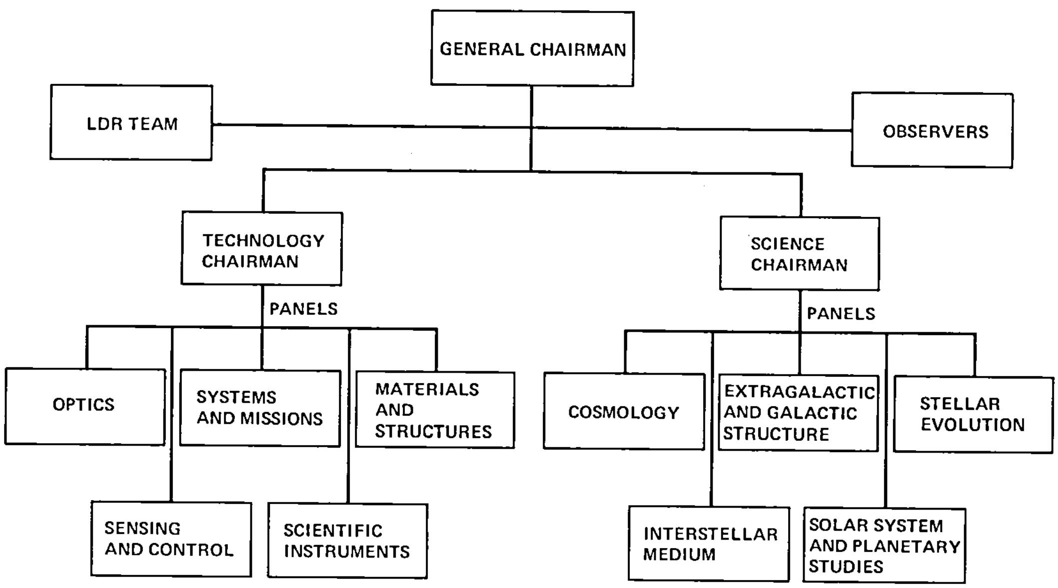

Figure I-1.– Workshop Organization.

Prior to the Workshop, a science team, composed of the Science Panel Chairman and various NASA and JPL scientists, provided the representative LDR Science Performance Goals shown in table I-1. The Systems and Missions Panel then convened one day prior to the other technology panels to establish representative LDR systems approaches (System I and System II), also shown in table I-1. These systems requirements served as a starting point for Workshop deliberation, and were iterated between the scientists and technologists during the course of the Workshop, with the Systems and Missions Panel acting as the interface.

TABLE I-1.– LDR REPRESENTATIVE SYSTEMS GOALS

Characteristics	Science performance goals	System I	System II
Diameter, m	30	30	10-15
FOV, arcmin	10	1-10	1-10
F/No (system)	TBD	TBD	TBD
λ-limit, μm	30	30-50	30 (10 desired)
Light-bucket blur circle, arcsec	0.2	TBD	TBD
Sensitivity to background, K	<200	<200	<200
Absolute pointing, arcsec	0.5	0.05	0.1
Jitter, arcsec	1.05	1.02	1.05
Slew, deg/min	20	20	20
Raster scanning	N/A	TBD	TBD
Integration period	N/A	TBD	TBD
Required orbit	None	TBD	TBD
Chopping	Yes	Yes	Yes
Polarization	Limited cross polarization	Limited cross polarization	Limited cross polarization
Sidelobes	Minimize near sidelobes	Minimize near sidelobes	Minimize near sidelobes
Sky exclusion, deg Sun, Earth	45-60	60	45-60
L/D (sunshade)	TBD	TBD	TBD
Limiting noise	TBD	TBD	TBD
Limiting noise level	TBD	TBD	TBD
Cryogenic cooling	Instruments only (0.2 K-50 K)	Instruments only (0.2-50 K)	Instruments only (0.2-50 K)
Lifetime, yr	10 yr total (2-3 yr revisits)	10 total (2-3 yr revisits)	10 total (2-3 yr revisits)
Deployment	Automatic or semiautomatic (one Shuttle)	TBD	Automatic or semiautomatic (one Shuttle)

The final set of Workshop-recommended LDR consensus systems requirements was compiled by Dr. P. Swanson (JPL) and are shown in table I-2. The rationale for changes between the LDR straw-man systems requirements and the LDR consensus systems requirements is described in Volume III of this report. The major detailed findings of the science panels shown in figure I-2 are described in Volume II of this report, and the detailed findings of the technology panels shown in figure I-2 are described in Volume III of this report.

TABLE I-2.– SUMMARY OF LDR CONSENSUS SYSTEMS REQUIREMENTS

Observational requirement	Functional requirement	Telescope requirement
Observe throughout region obscured by Earth's atmosphere	30 μm < λ < 1 mm diffraction limited (50 μm acceptable)	rms surface error <2 μm rms slope <1.5 μrad
Far-IR studies of:		
Galaxies at cosmological distances	Spatial resolution comparable to ground-based telescopes	D > 6.5 m @ 30 μm
Spiral structure in distant galaxies	$\lesssim$1 arcsec in far-IR $\rightarrow$ $D/\lambda > 2 \times 10^5$	D > 20 m @ 100 μm
Giant molecular clouds in nearby galaxies		
Protostars in our galaxy	Absolute pointing to HPBW/5 Pointing jitter to HPBW/10	$\lesssim$0.06 arcsec absolute $\lesssim$0.03 jitter
Observe faint objects at large distances	Sensitivity α D^2 number of sources α D^3 $\rightarrow$ D as large as possible	D $\gtrsim$ 20 m
	Spatial chopping to eliminate sky background to 1 part in 10^6	2 Hz, 1 arcmin spatial chopping
	Stray light at detectors below telescope emission	Limits view angle to Sun and Earth
	Minimize telescope background emission	Primary temp ≈ 150 K Secondary temp < 150 K Emissivity < 0.05 @ 100 μm < 0.01 @ 1 mm
Mapping extended sources, planets, molecular clouds, H II regions	1° × 1° raster scan $\gtrsim$3 arcmin IFOV	Scan mirror Array detectors Long focal length
Near-IR studies of high red shifted galaxies (Z $\gtrsim$ 3)	Spatial resolution $\lesssim$2 arcsec in 1 to 30-μm range ϵ < 0.1 in 1 to 10-μm range	Light-bucket operation at λ < 30 μm $\rightarrow$ surface error << 2 μm Micro roughness $<\lambda/40$ = 0.2 μm @ 10 μ λ = 0.2 μm @ 1 μ λ
Observe extra solar planets	Sidelobes < –40 dB at θ > 10 arcsec @ λ = 30 μm	Uniform illumination $\rightarrow$ –39 dB @ 10 arcsec Low scatter
Cosmic background	Detector noise limited at λ = 1 mm (background NEP <10^{-16} $WHz^{-1/2}$)	ϵ < 0.01 $\rightarrow$ roughness < 7 μm
Mission-related requirements	Single Shuttle launch	Deployable structure Panels <4 m diam Mass <27,000 kg
	10-yr lifetime Maximize viewing time Revisit capability	>750 km orbit $\gtrsim$20°/min slew
Maximum detector sensitivity throughout spectral range	Background-limited noncoherent detectors	NEP $\lesssim 10^{-16}$ $WHz^{-1/2}$ @ 10 to 100 μm NEP $\lesssim 10^{-17}$ $WHz^{-1/2}$ @ 100 to 1000 μm
	High-resolution spectroscopy $\Delta\lambda/\lambda < 10^{-6}$, 50 to 1000 μm	Coherent receivers with $T_{sys} \lesssim$ 1000 K Cryogenic systems, 0.1 K to 50 K

II. SCIENCE SUMMARY

A. INTRODUCTION

The Astronomy Survey Committee ("Field Committee") of the National Academy of Sciences recommended the LDR as one of the top missions for development in the coming decade, describing it as a telescope "of the 10-m class in space (designed) to carry out observations in the far-IR and submm regions of the spectrum that are inaccessible from the ground." The Field Committee further recommended that if the large telescope achieved the highest possible spatial resolution, important new observations could be made, especially in the fields of star and planet formation and cosmological studies. Since the atmosphere is completely opaque in the wavelength range from 30 to 300 μm, and largely opaque from 300 μm to 1 mm, the recommendations pointed to the basic requirements which defined the LDR: an approximately 10-m-diameter telescope, diffraction-limited to about 30 μm, operating primarily between wavelengths of 30 μm and 1 mm.

The scientific meetings of the LDR Workshop at Asilomar amplified the scientific rationale for such a telescope, and used this rationale to iterate the basic telescope requirements and to provide more detailed telescope requirements. As anticipated by the Field Committee, the science rationale developed at Asilomar provided many specific examples of how the LDR will bring major advances to the fields of star and planet formation and cosmological studies of the microwave background. New and exciting possibilities which emerged at the workshop included cosmological studies of distant galaxies using the LDR as a light bucket in the near-IR and the search for planets around nearby stars. The star formation studies envisioned at Asilomar pointed to a larger telescope; a 20-m diameter was adopted as a technical goal which may be feasible and one which would bring 1-arcsec angular resolution at wavelengths near 100 μm. These same studies suggested relaxing the diffraction limit to perhaps 50 μm if the 30-μm performance was not significantly degraded. On the other hand, near-IR light-bucket detection of distant galaxies and the detection of planets at 30 μm required better mirror-surface accuracy and shorter wavelengths for diffraction-limited operation.

Summarized below is the scientific rationale developed at Asilomar in the areas of (1) the origin and evolution of stars and planets, (2) the structure of galaxies, and (3) cosmological studies. Following this is a summary of the key telescope requirements derived from this rationale. Figure II-1 tabulates the baseline scientific rationale and selected technology requirements for a 20-m LDR. Shown in this figure are the science rationale, selected technology requirements, and observing constraints imposed by the Earth's atmosphere.

B. THE ORIGIN AND EVOLUTION OF STARS AND PLANETS

Understanding the physical processes which control the formation of stars is one of the challenges of modern astrophysics. Stars form in condensations of gas and dust within giant molecular clouds which, in turn, may form from large atomic clouds in the disks of galaxies. It is thought that the collapse of these condensations under their own self-gravity leads to the formation of prestellar disks from which stars and planets are born, a process marked by increasingly complex cosmic chemistry.

Understanding the process of star formation will ultimately require a detailed knowledge of how the tenuous, cold material in the molecular clouds is transformed into objects of stellar density. The same molecular clouds which give birth to stars also hide the process from optical viewing, because the dust

prevents any visible radiation from escaping the cloud until after the stellar birth is substantially complete. Radio and IR radiation, however, penetrates this natal shroud.

Furthermore, the earliest stages of star formation are characterized by low temperatures. The relevant temperature range of 10–1000 K is one which is most sensitively probed by IR and submm observations. The bulk of the dust emission, which generally includes most of the power radiated, falls into this range. Additionally, a large collection of molecular and atomic lines will be excited at these temperatures and will provide important data about the composition and motion of the gas.

Amazingly, the crucial epoch of star formation, that of the collapse of a gas and dust condensation of size 0.1 light years (ℓ.y.) to a protostellar disk of size 10^{-4} ℓ.y., has not yet been directly observed. The angular resolution and sensitivity of existing telescopes is insufficient to witness this epoch. An LDR with angular resolution of 1 arcsec at 100 μm could resolve and detect collapsing condensations with spatial resolution of 10^{-2} to 10^{-3} ℓ.y. at the distance of the nearest star-forming regions. If the LDR eventually became part of an interferometer, protostellar disks out of which planets form would be resolvable.

The problem of planetary system formation is closely-coupled to that of star formation. Perhaps the fundamental mystery in planet formation is the likelihood that planets will form around a star. The answer to this mystery lies in observing a variety of stars and determining how many have planets. No extrasolar planet has yet been directly observed. A 20-m LDR may be able to directly detect nearby extrasolar planets at wavelengths near 30 μm. The stellar cycle is completed as stars age and eject their outer layers back into interstellar space. enriching the medium with elements heavier than hydrogen from which subsequent generations of stars and planets will form. LDR can also look for excesses in the abundances of heavy elements that may mark regions such as the galactic centers, where star formation may have proceeded at high rates.

LDR will also contribute to our understanding of the origin and evolution of the solar system by providing new and unique information on the composition of comets and planetary atmospheres. In this way LDR offers the potential of bridging the gap between solar system studies and the broader questions of stellar evolution.

C. THE STRUCTURE OF GALAXIES

Galaxies are primarily stars held together by their mutual gravitational attraction. High-angular-resolution studies of the global patterns of star formation in galaxies therefore reveal much about the efficiency, triggering mechanisms, and history of star formation, and about the relation of star formation to the local environment. A 20-m LDR will resolve spiral arms, where massive star formation is apparently triggered, out beyond the large cluster of galaxies in Virgo. The angular resolution and sensitivity of a 20-m LDR allows detection and resolution of atomic, molecular, and ionized clouds in nearby galaxies; these clouds may mark sequential stages in the process of star formation. Rapid star formation in galactic nuclei can be a source of great energy and may explain the large luminosities of certain "active galaxies." Other galactic nuclei such as quasars apparently have more unusual sources of energy (e.g., black holes), and the angular resolution of LDR can distinguish star-forming regions from those regions. The LDR, therefore, by studying the efficiency and large-scale pattern of star formation will help reveal the underlying factors which determine the morphology and the basic evolution of galaxies.

D. COSMOLOGICAL STUDIES USING LDR

The importance of IR and submm wavelengths for cosmological studies is a consequence of the expansion of the universe; more distant objects are receding at greater velocities, so that the astrophysical information carried by their intrinsic radiation is shifted toward longer wavelengths. The most striking example of this effect is the cosmic background radiation, the highly red-shifted relic of the cosmic fireball in which the universe was born. This radiation permits us to look to an epoch and thus probe the structure of the early universe when the universe was only 1/1500 of its present size and 1/30,000 of its present age.

The presently observed temperature of this radiation is 3 K, so that its energy density peaks near a wavelength of 1 mm; a significant fraction of the energy lies at wavelengths $<$1 mm. LDR will give unparalleled access to this wavelength range on a finer spatial scale (10 arcsec) than is now attainable. The scale of the structure and fluctuations of the cosmic background radiation are expected to be very small on this scale – the radiation is remarkably isotropic on the larger scales that have been studied – but these small-scale fluctuations carry valuable information about galaxy formation in the early universe.

Observations between 600 μm and 3 mm of the effects on the cosmic background radiation of hot gas in clusters of galaxies (Sunyaev-Zeldovich effect) may, in association with observations of X-ray emission from the same gas, provide a new method for determining Hubble's constant. This quantity, which is the ratio of an object's recession velocity to its distance, defines the fundamental distance scale and age for the universe.

Other cosmological studies will be carried out if LDR can operate in a light-bucket mode in the near-IR ($\lambda \approx$ 1–4 μm) with a blur circle of approximately 1 arcsec. At these wavelengths LDR is well suited for the study of distant galaxies that are so highly red-shifted ($Z > 3$) that the peak of their energy distribution is moved into this wavelength region. The angular size and spatial distribution of these very distant galaxies, when compared with observations of nearby galaxies, will help determine the basic geometry of the universe (i.e., whether the universe is open and will continue to expand forever, or whether it is closed and will eventually collapse) and constrain the evolution of the intrinsic properties of the galaxies. The high sensitivity of LDR in the light-bucket mode makes it the only telescope that could push such studies of red-shifted galaxies to the confusion limit at which more than one galaxy is seen along each line of sight. No telescope will ever be able to see more distant galaxies than LDR with 1-arcsec angular resolution at 1–4 μm and mirror temperatures of 200 K or cooler.

E. TELESCOPE REQUIREMENTS DERIVED FROM THE SCIENCE RATIONALE

The scientific objectives envisioned at the Asilomar LDR Science Workshop led to overall LDR design requirements concerning the operational wavelengths, telescope diameter, mirror-surface accuracy, mirror temperature and emissivity, instrument complement, and field of view (FOV). We summarize below the main telescope requirements and the scientific rationale which drives these requirements (see fig. II-1).

1. Operational Wavelengths

The fundamental wavelength band of interest is from 30 μm to 1 mm, but light-bucket operation in the 1- to 4-μm wavelength region may also be of considerable importance. The formation of stars and planetary systems is best studied from 30 μm to 1 mm, where we receive most of the radiation from these systems. Important cosmological studies require operation near 1 mm, where the microwave (3 K) background peaks,

or in part of the near-IR region from 1 to 4 μm, where the starlight from distant galaxies is shifted by the expansion of the universe. The region of 30 μm to 300 μm and certain long-wavelength bands are completely obscured to ground-based telescopes. The regions from 300 μm to 1 mm and from 2 to 5 μm suffer from serious atmospheric absorption or noise. For these bands, a space-based telescope is required.

2. Telescope Diameter

A telescope diameter of at least 20-m was chosen to produce diffraction-limited spatial resolution of 1 arcsec at 100 μm, a resolution which allows direct comparison with ground-based optical measurements. Interesting phenomena of this angular size include protogalactic perturbations of the microwave background, cosmologically distant galaxies, spiral patterns in distant galaxies, giant molecular clouds (sites of star formation) in nearby galaxies, nearby protostars, and planet-star separations in the closest stars. In addition, only the collecting area of such a large telescope provides the sensitivity required, for example, to detect planets orbiting nearby stars or detect signals from distant galaxies.

3. Primary Reflector Surface Accuracy

The mirror surface should provide diffraction-limited viewing for wavelengths longer than 30 to 50 μm and a blur circle of about 1 to 2 arcsec at 1 to 4 μm. The former is driven by studies of star formation, since the hot dust near the protostar radiates copiously near 30 μm. (Wavelengths shorter than 30 μm may be observable through atmospheric windows from large, ground-based telescopes.) The light-bucket blur-circle requirement arises because cosmologically distant galaxies are of this size and are spaced extremely close together, often overlapping.

4. Primary Reflector and Secondary Mirror Temperature and Emissivity

The primary reflector and secondary mirror should be as cool as possible, and the emissivity of the reflector and mirror at wavelengths of ~1 mm should be as low as possible. Since the secondary mirror emission quadruples the primary mirror emission, cooling the relatively small secondary mirror to $\lesssim$150 K would reduce the overall emissivity by up to a factor of 1.4. Cooling the reflector and mirror significantly increases the sensitivity of the telescope in the near-IR and makes possible the observation of highly red-shifted galaxies. The Asilomar Workshop set 150 to 200 K as possible goals to be achieved by passive cooling. The sensitivity to the microwave background at 1 mm is best enhanced by using low-emissivity materials for the reflector and mirror. The Workshop took $\epsilon = 0.01$ at 1 mm as a practical design goal.

5. Instrumental Complement

The scope of the scientific investigations for LDR translates into an extremely broad range of instruments. Some order can be found by grouping the instruments by resolving power (table II-1). Within each regime of resolving power, several instruments will be required to cover the wavelength range of interest. Because the exact nature of many of the instruments has not been established, they are referred to by generic identities.

The large number of instruments will make it important to find ways to share common elements. For example, the three heterodyne front ends in the Ultra-High Resolving Power Spectrometer will share common back-end electronics. Some of the photometric arrays might also be used for spectroscopic devices. Despite these possible economies, the instrument requirements represent a technological challenge.

TABLE II-1.– INSTRUMENTS FOR USE BY LDR

Instrument	R	Wavelength range, μm
Photometric imaging array (with four arrays)	$3\text{-}10^2$	1-5 30-120 100-200 100-1000
Medium-resolving-power spectrometer (with three arrays or single detectors)	$10^2\text{-}10^3$	1-5 5-30 30-120
High-resolving-power spectrometer (with three arrays or single detectors)	$10^4\text{-}10^5$	1-5 5-30 30-220
Ultrahigh-resolving-power spectrometer (with three heterodyne front ends)	$10^6\text{-}10^7$	521-654 361-455 110-157

Continued interaction between the astronomers and technologists will be essential for assigning priorities and assessing technological possibilities.

6. Field of View

To study extended sources, a FOV greater than 3 arcmin is required. With its unprecedented spatial resolution, LDR will serve as a prime imaging device for the submm/far-IR wavelength region. Planets in the solar system, star-forming condensations in nearby molecular clouds, ionized gas around newly formed hot stars, and galaxies all have sizes of typically 1 to 10 arcmin.

III. TECHNOLOGY SUMMARY

A. INTRODUCTION

The scientific meetings of the LDR Workshop at Asilomar amplified the scientific rationale for a 10-m class telescope, recommended by the 1981 Field Committee report. Prior to the Workshop, a science team, composed of the Science Panel Chairmen and various NASA and JPL scientists, provided the representative LDR Science Performance Goals shown in table I-1. The Systems and Missions Panel then convened one day prior to the other technology panels to establish a straw-man set of LDR systems approaches (System I and System II), also shown in table I-1. This set of requirements was given to the scientists and technologists during the course of the Workshop, with the Systems and Missions Panel acting as the interface. As shown in figure I-2, the technology portion of the Workshop was divided into four other panels – Optics, Sensing and Control, Structures and Materials, and Science Instruments. Appendix A contains a complete list of all participants of the technology portion of this Workshop. The straw-man set of LDR systems requirements was supplied to each technology panel. The charter for the technology panels was to identify the relevant technologies within their discipline for LDR, and to assess the current and projected state of the art of these technologies.

The general areas of consideration for each panel are shown in table III-1. Wherever the technology fell short of LDR requirements, the technology panels were to recommend development programs for that technology, or alternative technologies, or a change in LDR requirements. This section will summarize the findings of each of the five technology panels.

TABLE III-1.– AREAS OF CONSIDERATION – TECHNOLOGY PANELS

Panels	Areas of concern
OPTICS	Configuration, primary reflector and secondary mirror characteristics, figure control, optical materials, coatings, producibility.
MATERIALS AND STRUCTURE	Support structure, dynamics, deployment, thermal control, vibration control, optical materials, fabrication, testing, sunshade.
SENSING AND CONTROL	Acquisition, tracking, pointing, vibration control, adaptive optics, figure sensing.
SCIENCE INSTRUMENTS	Photon detectors, arrays, bolometers, mixers, spectrometers, heterodyne receivers, local oscillators, cryogenics, signal processing, smart sensors, cameras, cold electronics, cold optical elements, mechanisms.
SYSTEMS AND MISSIONS	Conceptual design, orbits, budgets, power/weight/volume/telemetry constraints, operations, contamination, simulation, demonstration, second level technologies, technology oversight.

B. SYSTEMS AND MISSIONS PANEL SUMMARY

1. Introduction

The charter for the Systems and Missions Panel was to define systems requirements and technology issues and to act as the interface between the various technology panels. Another principal goal of the Systems and Missions Panel was to provide the interface between the science and technology sides of the Workshop by translating the science goals into requirements. Consequently, the representative requirements (System I and System II) were arrived at after analyzing the science goals. System I involved a 30-m-aperture LDR and System II involved a 10- to 15-m-aperture LDR. These two approaches are shown in table I-1. Following this, all of the Technology Panel Chairmen discussed several different LDR configurations other than the baseline axisymmetric Cassegrainian concept. These included a rectangular aperture (slot), a diluted aperture, a radially degraded aperture, and electrostatically figured membranes. Except for the diluted aperture, all other concepts were recommended for further study. The complete charter for the Panel is as follows.

- Straw-man systems requirements (from science goals – conceptual design approaches)
  - Mission considerations/implications
    - Orbit/operational considerations
    - Power/weight/volume/telemetry constraints
    - Deployment/assembly/construction trades
    - Lifetime/reliability/refurbishment potentials
    - Contamination (technology considerations)
    - Automation (technology considerations)
    - Smart sensing (technology considerations)
    - Cost
  - Budgets
    - Photon noise/mass/wavefront error
    - Tolerances
    - Other
  - Performance considerations
    - Diffraction – limit versus diameter
    - Light bucket
    - Chopping
    - Other
  - Technology assessment implications on systems design testing/demonstration/ proof of concept/simulation

The systems requirements evolved and expanded throughout the week, resulting in the consensus requirements shown in table I-2. The Systems and Missions Panel believes that these requirements are likely to be the most demanding, self-consistent requirements that can be reached if an initial operating capability for LDR in 1995 is to be realized. While these consensus systems requirements may not provide scientists with all of their initially desired observational goals (e.g., the resolution possible with a 30-m aperture), these requirements do come close to the desired goals and actually offer observational enhancement in some areas. The general optical configuration (mirror sizes, focal numbers, and FOV) was influenced by a number of systems and technology considerations. For example, a 30-m-aperture telescope would be very difficult in terms of mass and volume constraints to fit into a single STS launch. This size was judged to be nearly impossible in the near-term by the Panel after considering several factors: (1) the mass, cost, and development schedule of the necessary sophisticated deployment mechanism; (2) the on-orbit stay time needs for erection and for the resultant extensive life-support requirements and added support mass; and (3) the very

stringent mass budget influencing all technology disciplines. Hence, a 20-m-diameter baseline was subjectively decided to be a reasonable size in the LDR time frame. For a more detailed discussion of the rationale that led from the initial systems requirements to the consensus systems requirements, see Volume III of this report.

2. Budgets

When assessing the consequences of the systems requirements on the overall concept, the panel arrived at three budgets: (1) an allocation of available system mass to various subsystems and components, (2) a system photon noise budget, and (3) a wavefront error budget based on the 30-μm diffraction-limited system.

The mass budget shown in table III-2 was developed as a baseline for the technology panels to consider. This very cursory mass allocation indicates how marginal it may be to package a 20-m LDR in a single Shuttle launch constrained to 27,000 kg. The 7000 kg allocated to the primary reflector assumes segments with areal densities of approximately 22 kg/m^2. This small number is well beyond the state of the art and represents one of the leading technological challenges for LDR.

The system photon noise budget requires the primary reflector and secondary mirror to be 150 K and 125 K, respectively. Temperature uniformity on the primary reflector and secondary mirror surfaces must be kept at $\leqslant \pm 1$ K. Scattered light (5 μm to 2 mm) must be $\leqslant$20% of all photon emission from the primary reflector segments. Figure III-1 shows the noise equivalent power (NEP) (W/Hz$^{-1/2}$) as determined by various individual noise sources, compared with the NEP provided by several detectors.

A total wavefront error budget was determined to be no more than 2 μm rms in order to provide a diffraction limit at 30 μm (Fig. III-2). The optical errors in the LDR are associated with these major sources: the primary reflector, secondary mirror, and individual instrument optics. The allocation for each of these

TABLE III-2.– LDR MASS BUDGET

Element	Mass, kg
Primary reflector	7,000
Sunshield and support structure	720
Tube/truss spiders	600
Secondary mirror and support assembly	50
Control (1.0 kW)	
Actuators	200
Sensors	200
Computer/electronics	200
Pointing system	500
Backup truss for primary reflector	3,000 (cell and back frame)
Equipment, CMG, solar panels (1.0 kW)	3,000
Instruments, cryogenics (1.5 kW)	3,500
Launch and deployment fixtures	2,000
Total	20,970
Propulsion	5,000
Margin	1,030
Total	27,000

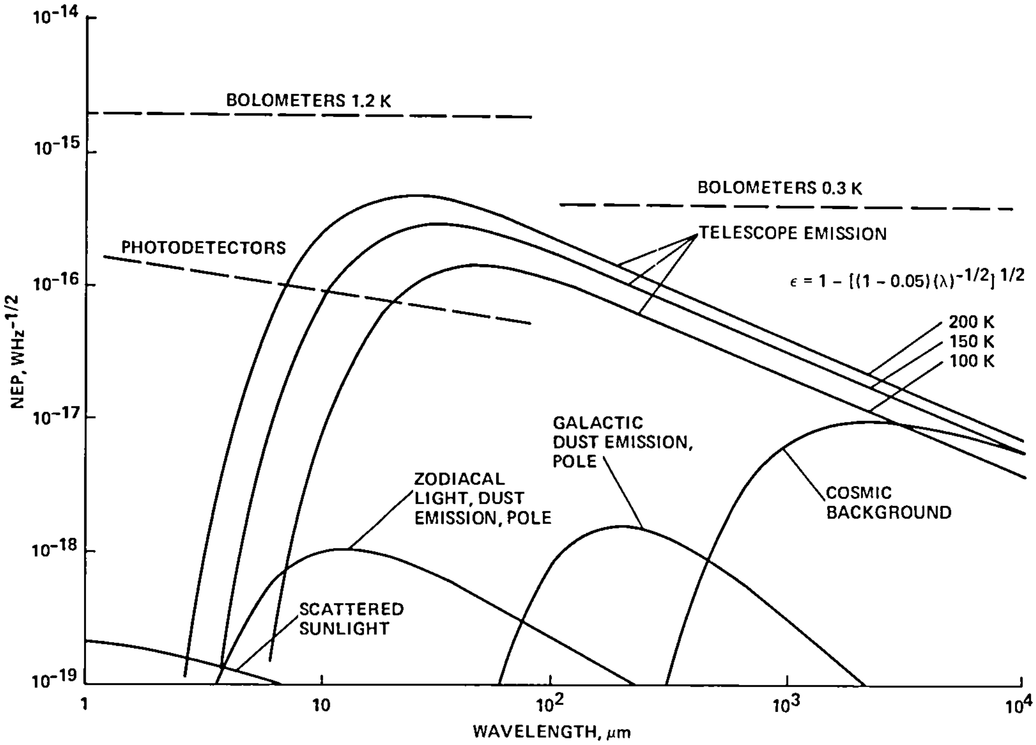

Figure III-1.— NEP versus wavelength (bolometers and photodetectors compared with background).

individual optical elements is 1.5 μm rms for the primary reflector, 1.0 μm rms for the secondary mirror, and 0.5 μm rms for the science instruments.

3. LDR Representative System Concept

In response to the LDR consensus systems requirements and budgets mentioned above, an LDR representative system concept resulted, as shown in figure III-3. The optical configuration is an axisymmetric Cassegrainian with the focus located near the vertex of the primary reflector. This reflector is composed of individual segments controlled to form a single image. The exact number and size of these segments are not yet known. Fine steering and spatial chopping are accomplished by small rotations of the reactionlessly mounted secondary mirror.

Additional optical elements in the scientific instruments are required to form pupils and FOV of the desired size, focal lengths, etc. A cylindrical thermal shade, probably internally baffled, protects the optics from stray light and varying thermal inputs from the Sun and Earth.

Main structural elements are composed of graphite/composite tubes in a tetrahedral truss arrangement. Control momentum gyros (CMG) are used for slew and tracking, and an offset guidestar system is used for pointing and control. A spacecraft bipropellant rocket brings LDR to orbit following Shuttle deployment.

4. Systems Issues and Analyses

Several topics were considered to be of special interest and were specifically addressed by the Systems and Missions Panel. The topics were (1) light-bucket operation, (2) chopping, (3) orbit considerations,

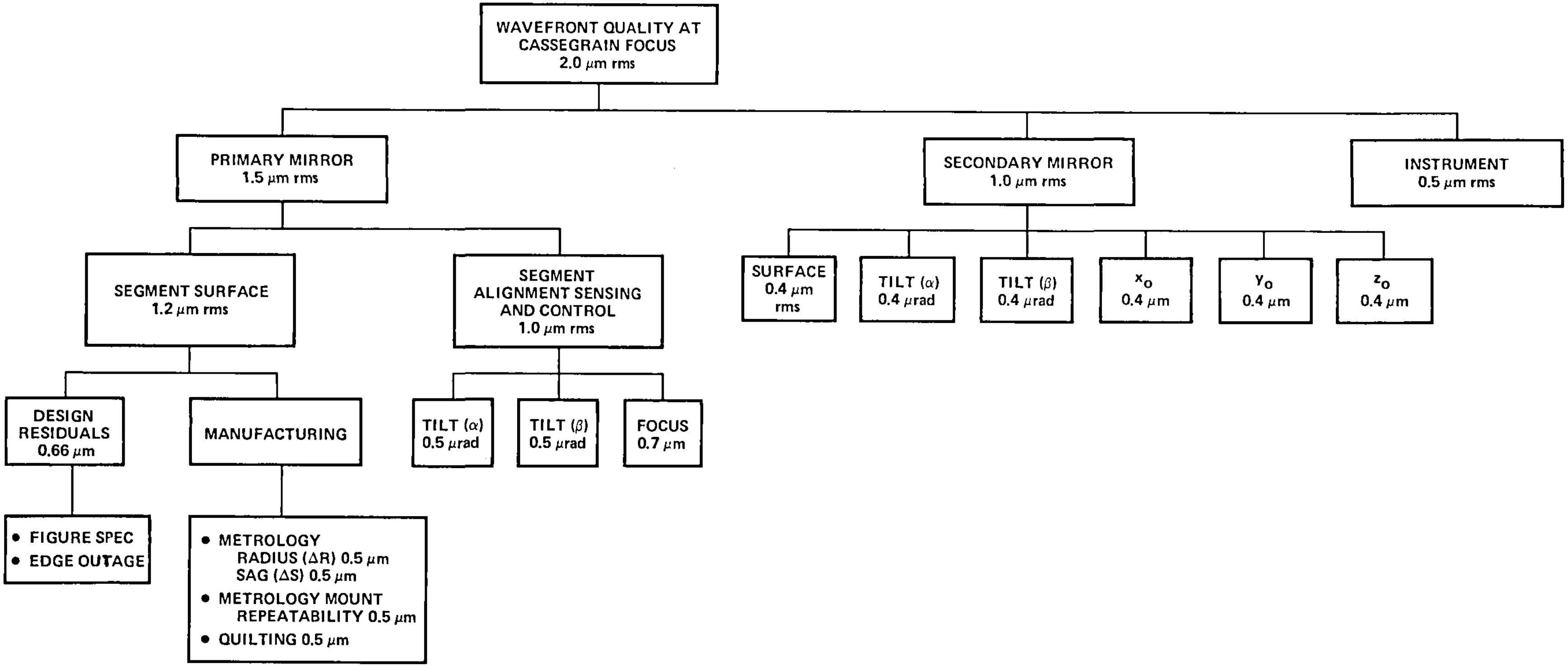

Figure III-2.— Wavefront error budget.

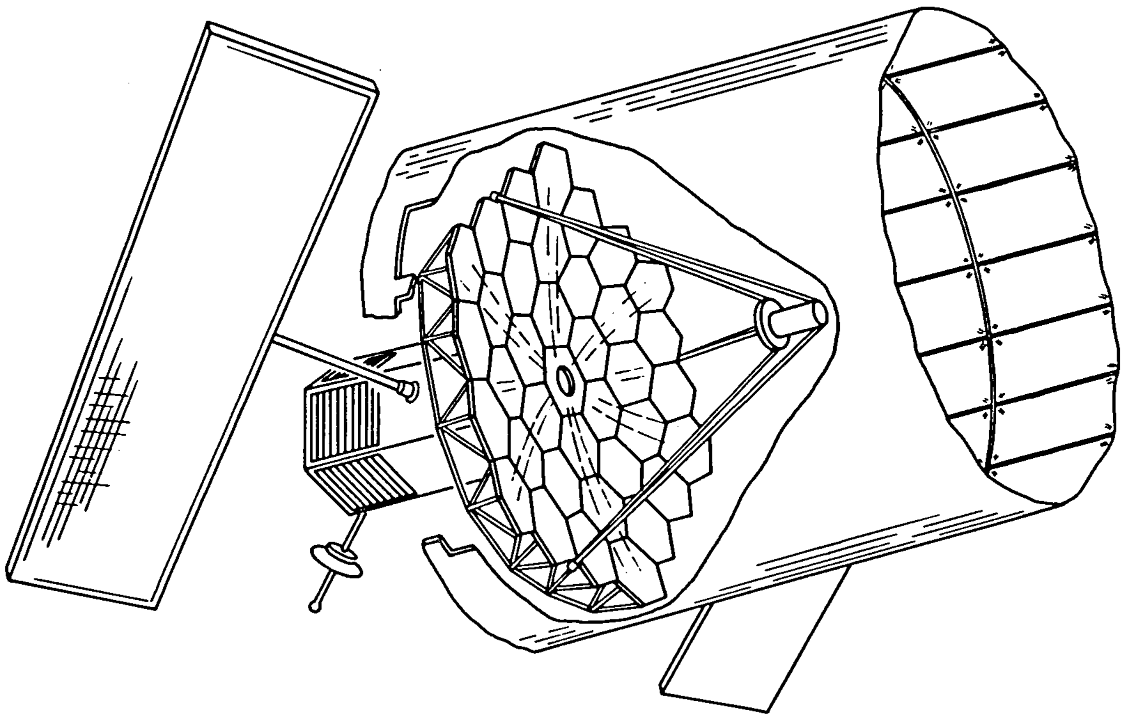

Figure III-3.– LDR representative system concept.

(4) lightweight monoliths for LDR, (5) thermal shade concepts, (6) thermal-control technology, and (7) power considerations.

a. *Light-bucket operations*– The light-bucket operation below the diffraction limit corresponds to the geometric optics limit where surface quality of the primary reflector surface dictates the image quality. The Panel concluded that seemingly loose light-bucket image quality requirements, in particular the small surface slope requirement, will set more stringent primary reflector segment fabrication tolerances than the sharper image quality requirement demanded for longer-wavelength, diffraction-limited operation. Figure II-1 shows the light-bucket operation from 1 to 30 μm; from 1 to 4 μm, the desired blur circle equals 1 to 2 arcsec.

b. *Chopping*– Chopping is required in the IR range for work from within the atmosphere because one is attempting to detect a weak signal in the presence of large and fluctuating background emissions from the atmosphere and optics. On existing telescopes, chopping is most successfully carried out by "wobbling" the secondary mirror. For LDR, however, this has disadvantages. Unfavorable dynamical consequences and possible degradation of image quality may result from wobbling the large and massive secondary mirror. Because of this, chopping methods were discussed with the LDR configuration and tentative conclusions were reached, including the following:

(1) Chopping by moving a mirror within the optical train may not be required for many LDR investigations. The required chopping frequency may be sufficiently low in these cases that chopping by moving the entire telescope may suffice.

(2) A stable thermal environment will help alleviate the chopping requirements for LDR.

(3) If the thermal environment is sufficiently stable, the need for chopping may arise because of other circumstances (e.g., detector properties) rather than background variations.

(4) Chopping by wobbling the secondary mirror may not be necessary or desirable, and alternative schemes (e.g., reimaging systems) should be explored.

c. *Orbit considerations–* From a scientific standpoint there are no strong preferences affecting the choice of LDR orbit, at least from a "preproject technology program" view. However, orbit choice does strongly affect the following mission aspects and deserves attention when design tradeoffs are considered: sky viewing constraints, the telescope thermal design, the detector radiation environment, spacecraft propulsion, mass to orbit, service requirements (acceptability), and the mission timeline (slewing, propulsion, and thermal control maneuvers). Current baseline LDR orbit options are discussed in Volume III of this report.

d. *Lightweight monoliths for LDR–* The current state of the art of lightweighting the primary reflector segments was discussed. The process of completing surfacing prior to lightweighting was identified as not a "standard practice." It appears that the monolith design concept discussed may be applicable to LDR (see Volume III of this report).

e. *Thermal shade concepts–* A representative shade concept was derived by the panel for a 60° viewing exclusion angle from the Sun and for a 45° exclusion angle from the Earth. Shade geometry, viewing constraints, stray light and thermal analyses, and orbit choice were all recommended for further study.

f. *Thermal control technology–* Thermal control to meet the requirements of 150 K cooling for the primary reflector and 125 K cooling for the secondary mirror was thought by this Panel to be a potential technology driver for LDR.

g. *Power considerations–* Power systems were one critical discipline which did not fall under the purview of any panel. At this time, power needs appear particularly demanding and disturbing in their potential effect on systems. Total continuous power needs call for about 10 kW, most of which is needed to run closed-cycle refrigerators. This capacity entails 150-200 m^2 of solar panels and a total power subsystem mass of about 4000 kg. As this is considerably more than the allocated mass, one must hope for considerable technological growth here or accept a different concept and perhaps a reduced mission capability. Stored cryogens would reduce the power requirement, but they must be replenished at regular intervals.

5. Development Plan

The Systems and Missions Panel recommended a development plan as shown in figure III-4. The plan was scheduled so that LDR would have demonstrated technological readiness before the start of flight hardware development. It was felt that the current pace of technology development would not be sufficient for a new start in 1989. An augmented technology program lasting 3 to 5 yr and costing $40-50 million was recommended to meet LDR technology needs. This is in addition to ongoing OAST efforts applicable to LDR.

Some of the recommendations of the Panel were: continued science participation in the technology effort; a major systems study to look at system level trades (orbit, mass, viewing, etc.); a ground proof-of-concept demonstration at the end of the technology initiative; and a possible flight demonstration.

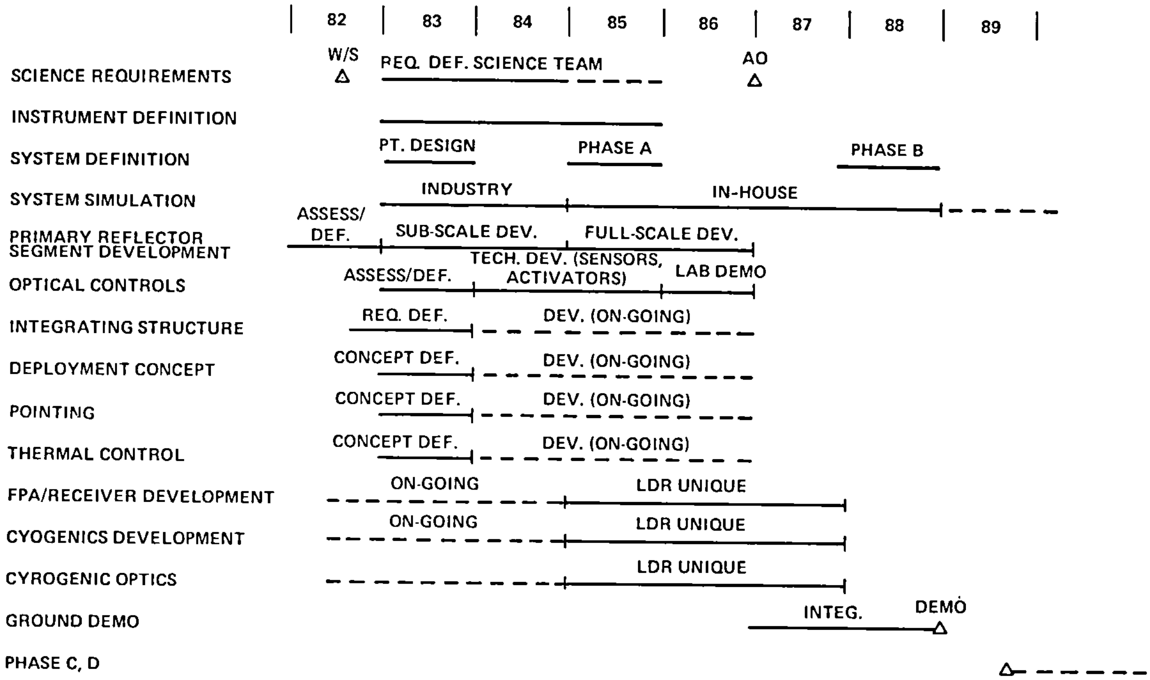

Figure III-4.– LDR development plan.

Of all the technology areas, research in lightweight, inexpensive, easily replicatable primary reflector segments was given the highest priority and a major development program was urged starting in 1983. The next most pressing technologies were optical controls and science instruments. The need for a systems simulation capability was also given a high priority. Several topics were identified as needing further study, analysis, and definition:

a. Polar (terminator) versus Low-Inclination Orbit tradeoffs.

b. Advantages and disadvantages of off-axis optics.

c. Quantity effects of Sun exclusion angle on Sun/Earth thermal shade weight and inertial problems.

d. Derivation of a matrix of user needs as a function of telescope wavelength.

e. A review of possible chopping alternatives and effects.

f. A look at system performance as a function of weight, cost, and complexity.

g. A description of system and operational consequences of the rectangular aperture (slot) option.

h. Refinement of light-bucket analysis techniques.

i. Study concepts for an evolutionary LDR.

j. A study of how a manned space station might benefit LDR development.

C. OPTICS PANEL SUMMARY

1. Introduction

The first main concern of the Optics Panel was how a primary reflector could be made to meet the desired goals. There is no proven technology that can meet the required weight, thermal and mechanical stability, and surface figure. Because the surface is so large, cost and production time are serious considerations. The second main concern of this Panel was that serious consideration be given to noncircular apertures, interferometric options, and off-axis geometry.

2. Primary Reflector Construction

There was a consensus among the Panel that a reflector made up of some form of lightweight glass segments was the most viable approach. To some extent this consensus reflects the expertise of the panel members, but it also reflects the direction that this technology is being driven by military needs for reflectors to operate at shorter IR wavelengths.

The Panel reviewed the development of several methods of fabricating lightweight segments of very-low-expansion glass by frit-bonding (e.g., Corning, Kodak) and by machining, followed by acid etching (e.g., Itek). Industry is tooling up to make segments of 4-m diameter, and to develop machines for rapid precision grinding of off-axis segments (to $\sim$1 μm rms) and computer-controlled polishing. It seems that this technology for making high-quality segments for a $\sim$100-m^2 reflector will be practical and available relatively soon. However, the technology for making a reflector of $\sim$1000 m^2 is uncertain. The segments have to be much lighter and flimsier (for a single or double Shuttle launch), and the cost and schedule of production for making and figuring this huge area could be prohibitive.

This Panel reviewed other technologies that might lend themselves more easily to the large area and somewhat reduced tolerances of the LDR. Most of the alternatives involve materials that are not so thermally forgiving as the structured ultra-low-expansion (ULE) segments. Their practicality will depend on the thermal environment – the operating temperature, and its temporal and spatial variations. For this reason this Panel identified a study of the thermal shade, orbit, and thermal design as a very high priority for tradeoff against reflector technology.

For a reasonably benign temperature environment, borosilicate and the Cervit-Zerodur families should be considered as alternative glasses. The latter, partially devitrified glasses, can be slumped into curved sheets, but because they are thin their figure is dependent on minimizing front-to-back temperature gradients, even though the coefficient of thermal expansion (c.t.e.) is very low. Borosilicate can be fabricated into deep lightweight structures more easily than the refractory ULE, but it again needs low thermal gradients because of its larger c.t.e.

The Panel was uncertain about the value of graphite epoxy and other composites for LDR segments, given that the goal of diffraction-limited operation is 30 μm. Because of the inhomogeneity in the c.t.e., it seems likely that segments using graphite epoxy would have to be tested at the operating temperature during figuring. There was also concern about the long-term stability of the material (e.g., the sensitivity to humidity). Nevertheless, the possibility of simple replication of very light, rigid, finished segments from precision masters, as is being tried by Dornier and the University of Arizona, remains tantalizing. Hard numbers on current performance are needed to see if this approach is worth pursuing further. If LDR favors a larger-area, less-precise mirror, then this approach could be very competitive, as could all-aluminum honeycomb segments. Aluminum is quite homogeneous, but its very high c.t.e. (10 times that of borosilicate) would seem to

rule it out for use at 30 μm. There are still further exotic technologies, such as stretched membranes. A careful general review from an impartial source would be valuable.

The area of segment figuring was felt to be almost as problematical as that of developing a good substrate. Leighton (1978) has demonstrated the capability to measure an assembled dish to an accuracy approaching LDR's goal of 1 μm. Methods of figuring based on this type of axisymmetric turning, and on smaller numerically controlled fine-grind and polishing machines need to be evaluated.

Included in the discussions were the methods available to sense mirror figure and wavefront error, and to make corrections. While the principles for doing this are reasonably well understood, practical devices need to be demonstrated and questions of cost, weight, and control complexity are critical. For example, it is much easier to make light 0.5-m segments with the correct shape and adequate stiffness than it is to make 2-m segments, but the number of sensors and correcting actuators goes up by a factor of 16. This tradeoff can be addressed only if some specific concepts are worked out in some detail. The problem divides into that of getting the reflector initially into alignment (more difficult) and maintaining alignment during operation (less difficult).

The method to be used for wavefront sensing has a critical effect on segment specifications. If the wavefront is to be studied with visible or near-IR point sources using Hartman- (or Shack-) type methods or interferometry, then smooth, shiny segments are required.

3. Optical Configurations

The optical configuration of the LDR was also discussed; this area needs immediate attention in the form of optical designs. Reflectors that operate at the diffraction limit, such as radio telescopes, are often not simply made as round dishes, but spread out their collecting area in some way to improve spatial resolution. Rather than make the LDR the biggest round dish affordable, it may be preferable to organize it, for example, as two dishes to be used as an interferometer (with one going up first perhaps), or as an elongated aperture (e.g., 8 by 30 m instead of 15-m diam). Obviously, packaging and deployment are radically affected by the reflector geometry, and the options need to be explored soon. The major uncertainty identified by this Panel was the image quality that can be recovered from elongated apertures. It is well known that images with a resolution corresponding to the longest dimension can be recovered from a set of exposures at different orientations, but the tradeoffs in signal to noise ratios for point objects and diffuse fields need to be clarified. Other factors that need exploring are the demand for detector stability during a set of exposures, and feeds for beams that are not round.

Another optical configuration choice that must be explored early on is whether to use an on-axis or off-axis optical system. Off-axis systems are mechanically more demanding, but they offer improved diffraction pattern, lower thermal background, and an absence of standing waves at the longer wavelengths. Elongated apertures can be made off-axis relatively easily. Optical design and optimization is needed to explore the diffraction-limited fields that can be obtained with these different options. Off-axis or elongated apertures tend to make the longer telescopes, and correcting schemes with more than one secondary mirror should be explored to keep physical size down and field size up. A formal systematic study of design options is recommended.

D. SENSING AND CONTROL PANEL SUMMARY

1. Introduction

Sensing and control will constitute a major subsystem of LDR and will be critical to its success. The subsystem must perform several functions:

a. Provide slewing and pointing control for the entire telescope to subarcsec accuracy.

b. Provide active alignment, figure, and vibration control of a very large optical system.

c. Make the initial alignment of the optical system following deployment and periodically verify and adjust system alignment and optical performance during use.

The functions are interrelated and are also closely connected to other parts of the system. This close interaction requires that work on all these areas goes forward simultaneously, and because of technical uncertainties the work to meet these challenges should be undertaken as soon as possible.

It is particularly important that sensor, actuator, and control technology be well developed in advance of any decision on a final LDR configuration. There are many critical system tradeoffs, such as the size of the primary reflector segments versus the number of actuators required, that can be made only if the sensing and control technology is well understood.

2. Sensing and Control Technology

There are a number of sensing and control techniques of potential application to LDR. Many have been demonstrated in the laboratory, and a few have been used in flight programs, but none has been applied to a system the size and complexity of LDR. The state of the art with respect to the various functions of the sensing and control system is briefly identified below:

a. *Telescope pointing–* Although the requirements for pointing and tracking LDR will be numerically less demanding than those of the Space Telescope (ST), which will precede it in space, the size and flexibility of LDR will in fact make its pointing the most demanding task yet to be faced. Part of the necessary pointing technology for LDR will be provided by the high-precision control techniques of the SIRTF and the ST. Specific areas requiring new developments are (1) advanced large-aperture star trackers to achieve offset pointing from faint stars; (2) electro-opto-mechanical systems to transfer the line of sight to the main telescope; and (3) large, dynamically quiet, reaction wheels (e.g., magnetic bearing wheels).

b. *Figure sensing and control–* This requires the use of sensors and actuators, to measure and control accurately the position and orientation of the segments of the primary reflector and other optical elements of the system, and of control algorithms to process the sensor information and issue the appropriate actuator commands. Although this area has progressed significantly in recent years, LDR will require considerable technology development to achieve (1) a space-qualifiable system capable of sensing the large number of points required by LDR, and (2) reliable figure actuators which can be produced in large numbers (200–500) at reasonable cost.

c. *Telescope calibration and wavefront control–* At present there is a limited technology base to draw on for the initial alignment of the optical system and the periodic verification of system alignment and optical performance. The consensus of this Panel was that the initial alignment and periodic verification can be

be accomplished by pointing the instrument at a bright astronomical object and sensing the wavefront within the instrument. Although this is a common technique at wavelengths in or close to the visible, its extension to the wavelengths of LDR will require extensive developments.

d. *Attitude-figure-wavefront sensing and control integration—* Another significant technology issue is the interaction of the attitude, figure, and wavefront sensing and control functions into the required overall telescope pointing and stabilization. This will require development of extensive analytical simulation tools and validation through laboratory-scaled proof of concept to demonstrate functional capability and correlation of actual and predicted performance.

E. STRUCTURES AND MATERIALS PANEL SUMMARY

1. Introduction

The Structures and Materials Panel technology assessment with respect to the science requirements was based on a generic class of structural concepts. This class of concepts utilizes an array of rigid, precision, doubly curved, reflector elements (panels) that are supported by a stiff truss structure. This generic concept lends itself to active surface control by the addition of actuators between the reflector elements and support structure and to a variety of antenna configurations, with circular or rectangular apertures and on- or off-axis feeds.

Critical technology identification and characterizations were developed by means of a work breakdown structure that contained the specific disciplines needed to accommodate the subject development. Results of the LDR technology assessment worksheets provided the technology assessments, task descriptions, timelines, and estimates of resources.

The structures and materials technology with the highest risk identified was that of providing the highly accurate reflector elements. Technologies with moderate risk included structure deployment/erectable concepts and structural simulation and validation techniques. The need for low-cost, lightweight, high-surface-tolerance panels is clearly the technological driver for LDR from a structural/materials point of view. Ranges of performance were established for the reflector panels, with the limits defined as high probability of success on one end and the best that could be expected at the other. For example, panel weight goes from 10 to 20 kg/m^2, surface precision from 1 to 5 μm rms for panels from 1 to 2 m in size. The higher-precision panel requirements can probably be satisfied only by monolithic material technology whereas the other end of the range might be accommodated by advanced structural composite materials technology.

Structural concepts for space deployment or assembly are required for the primary collector and its thermal shield. The thermal shield, whose design is driven by the orbit, desired operating temperature of the reflecting surfaces and telescope geometry, is a larger structure than the reflector itself. The challenge of an attractive combination of the two major elements is great. Limits of potential performance must be established for specific concepts to accommodate the trades needed to determine the range of usefulness of deployment versus assembly and single versus multiple Shuttle flights. Current concensus suggests that one Shuttle flight might accommodate a deployable LDR about 15 m in diameter with an overall surface tolerance of 5 μm rms with reasonably high probability.

Analytical tools presently available appear to be adequate for the structural simulation of LDR concepts. However, technology for interactive analytic performance prediction and the refined materials characterizations needed for such analysis needs significant improvement.

2. Implications

The LDR reflector concept for a 30-m diameter reflector, in a 28° orbit, using 0.5 μm rms panels has significant implications regarding the number of shuttle flights, the approach for building the structure, the feasibility of manufacturing such high tolerance panels and the possible need for an active thermal shield. Current technology is not expected to accommodate a 30-m LDR in a single shuttle flight, even with moderate relaxation of panel surface requirements. The structural approach for accommodating a 30-m diameter LDR will probably be different than that for a 10 to 20 m structure. On-orbit assembly becomes more attractive as larger size structures are considered. The desired surface tolerance for the reflector panels is so demanding that the use of advanced structural composite materials is probably prohibited and monolithic glass technology may have to be considered. The 28° orbit is so much more severe than the baseline polar orbit (90°) that baffles, orbit slews, and/or active shielding techniques may be required.

The overall viewpoint is that the 30-m-diameter (or even 20-m-diameter) LDR reflector poses technology difficulties that are great indeed. Of course, the state-of-the-art will be improved and the perceived expected advancement in capability will improve as the technology programs defined by the assessment worksheets are carried out. It must be emphasized, however, that the needs exceed current capabilities by orders of magnitude in several areas. The technology program therefore must be monitored and modified along with a companion effort for the science program.

F. SCIENCE INSTRUMENTS PANEL SUMMARY

1. Introduction

None of the candidate instruments discussed at the Workshop can be built at this time, but it is reasonable to expect that with sustained developmental progress and breakthroughs in some areas, high-performance imaging and spectroscopic instruments will fly on LDR. The necessary technology work falls into the general categories of heterodyne detection, direct detection, and refrigeration. Specific tasks are unique to NASA astronomical requirements; no significant technological progress relevant to LDR needs should be expected from outside the Agency. A list of technical topics discussed by the panel is included in table III-3.

TABLE III-3.– TECHNICAL TOPICS – SCIENCE INSTRUMENTS PANEL

Heterodyne detection	Direct detection	Instrument technology
Local oscillators (including power and frequency stability requirements) Mixers IF amplifiers Back-end electronics Calibration techniques Radiation effects EMI susceptibility Signal processing	Discrete photon detectors Discrete thermal detectors Arrays (photon and thermal) Cryogenic electronics Radiation effects Calibration techniques	IR filters and beamsplitters Instrument and detector cooling Cryogenic mechanisms Cryogenic optics Signal processing Multiple-instrument accommodations

2. Development Needs

Heterodyne systems for the submm are poorly developed. For the wavelength range near 1 mm, laboratory demonstrations with available components and a few astronomical observations have been carried out. For wavelengths less than ~400 μm, little more than ideas exist. A well-supported and coordinated technology program to improve the performance of local oscillators, mixers, and frequency multipliers should be set up now, so that a level of maturity can be achieved by the beginning of LDR construction. Because there is no previous space project experience for heterodyne systems at these wavelengths and there is negligible military interest, a serious effort by NASA is required. In most cases, the technology is not well enough understood to make definitive specific recommendations. For local oscillators, recent carcinotron developments are promising. This technology should be improved and extended to shorter wavelengths. New solid-state local oscillator concepts with higher output power should also be pursued, since this approach is far more compact and spaceworthy than tube technology. To varying degrees, each of the Schottky, bulk, and superconductor-insulator-superconductor (SIS) mixers have been demonstrated at or near 1 mm, but sensitivity and spectral coverage are limited. It is recommended that all of these ideas, in addition to innovative new approaches, be developed in parallel in the near-term, until clear choices emerge. Improved multipliers would allow established local oscillators to be shifted to otherwise inaccessible wavelengths. It may be that a program concentrating on SIS mixers, solid-state local oscillators, and frequency multipliers would provide the best ultimate performance throughout the 100- to 1000-μm range.

The LDR instrument concepts involving direct detectors emphasized multielement arrays. This area has at least a preliminary technological base at shorter wavelengths. Throughout the far-IR, it is expected that the imaging instruments will be background-limited. Some aspects of the problem should have been addressed by SIRTF before the LDR flight. The unique aspects of LDR, however, involve the emphasis on longer wavelengths, the large numbers of array elements, the need for low focal-plane power dissipation, and the large detector, filter, and instrument dimensions required. Significant technological developments will be required to produce space-qualified extrinsic Ge photoconductor and bolometer arrays for wavelengths greater than 30 μm. Work on a (~100 by 100) Ge:Ga array and a (~10 by 10) bolometer array was given the highest priority. Continuing advances in low-temperature, low-frequency cryogenic electronics should go hand in hand with detector advances.

It appears that LDR will require cryogenic cooling in the instruments which exceeds the state of the art. The need to absorb approximately 1 W at 2 K for a 3-yr period indicates a closed-cycle refrigerator which has significantly longer life, higher reliability, and lower temperature than exists at present. This power level would be reduced by allowing sections of the instruments to run at higher temperatures (~20 K), and by minimizing or filtering the instruments' entrance apertures. A suggested development plan in this area was to develop a low-temperature stage which would couple with higher-temperature, military-sponsored cooler technology. Primarily for reasons of mass and volume, a stored-cryogen system was judged to be impractical. In addition, improved 0.1 and 0.3 K cooling stages will be required if optimum bolometer performance is to be achieved.

The Panel recommended immediate support in all of these areas. Parallel approaches in a well-coordinated program will be required. This is especially true in the heterodyne area, in which the performance of components is tightly coupled (e.g., through mixer and local oscillator power requirements). For direct detectors, it is essential that significant technical progress be made under the SIRTF project. It was emphasized that ground-based and airborne observational experience with advanced instrumentation is an important part of technology development. It should be noted that an active LDR development program would also benefit ongoing and planned orbital, airborne, and ground-based IR/submm astronomy programs. A mix of industrial, academic, and government expertise should be brought to bear, and, since we have at least a decade before LDR flies, promising speculative ideas should be supported.

3. Instrument Complement

The Panel conceived seven instruments which seemed to satisfy most of the requests of the science panels. As was stated above, each would require some level of development, ranging from moderate to major. A heterodyne package to cover three spectral ranges at very high spectral resolution, with common back-end electronics, is included. One- and two-dimensional arrays of photon detectors and bolometers were envisioned in lower-resolution imaging instruments, and in dispersive and transform spectrometers. In the direct-detector instruments, the large size and throughput of LDR and the desire for reasonably high resolution imply large instrument dimensions; it was estimated that a volume of 4 m^3 and significant cooling loads would be required for the instrument package. A careful analysis of sensitivity and resolution requirements would be needed before the proper choice between heterodyne and direct detector systems for the 10^4 to 10^5 range of spectral resolutions could be made.

4. System Implications

It appeared that background subtraction in multielement arrays, which might eliminate the need for spatial chopping, was difficult, except for special cases with high signal-to-noise ratio. Device temporal instabilities and 1/f noise will not allow correction to the 10^{-6} level.

As was mentioned above, large instrument dimensions are anticipated. This implies many cubic meters of Shuttle bay volume, significant power to run the refrigerator (6 kW estimated), and significant cooling loads. The idea of a window or windows at the focal surface to protect the instruments from cryo-contamination was discussed; this would involve development for wide spectral coverage and cooling considerations.

It seemed that dynamic disturbances from the cryogenic refrigerator or interferometer instrument concept would be minor. However, the proposed equatorial orbit could introduce thermal and system instabilities that would rule out extended integration times.

TABLE III-4.– INSTRUMENTS PANEL TECHNOLOGY DEVELOPMENT TASKS

Refrigeration	
R-1*	Long-life, high-power, 2K refrigerator
R-2	0.1 and 0.3K cooling stages
Heterodyne	
H-1*	Heterodyne systems for 300-1000 μm
H-2*	Heterodyne systems for 100-300 μm
H-3	500 μm heterodyne arrays
Direct detectors	
D-1	Large (100 X 100) 30-120 μm arrays
D-2*	Large (10 X 10) 120-1000 μm arrays
D-3	120-200 μm arrays
D-4	Supporting technology for instruments

The following three tables were used in the Panel's final presentation.

In table III-4, the development tasks are listed in decreasing order of priority. While all this work was felt to be important, the tasks which were judged essential are marked with asterisks in the table. The phrase "heterodyne systems" encompasses local oscillator, mixer, and frequency multiplier components. Item D-4 includes a variety of important topics, including cryogenic electronics and multiplexers, IR filters and beamsplitters with larger dimensions and improved long-wavelength performance, cryogenic optics and mechanisms, arrays for wavelengths less than 30 μm, and improved long-wavelength photon detectors for both heterodyne and direct detection.

Table III-5 shows a possible instrument complement. For all wavelengths greater than 30 μm with modest ($<10^3$) resolutions, it was anticipated that background-limited performance could be achieved. At

higher resolutions and for 1- to 4-μm range, detector or preamplifier noise would be limiting. The heterodyne instruments are listed in order of increasing difficulty.

Concerns about the present LDR representative system configuration from an instrument perspective are listed in table III-6, with the primary problem areas marked with asterisks. Note that about 6 kW of thermal power, and not necessarily electrical power, would be required to run the refrigerator.

TABLE III-5.– INSTRUMENT COMPLEMENT IDEAS

Instrument	Spectral coverage	Comments
1. 100 X 100 Ge:Ga imager	30-120 μm	Filter wheel ~10^{-16} W/$\sqrt{Hz}$ NEP
2. 1 X 100 Ge:Ga spectrometer	30-120 m	• 3 gratings/3 Fabry-Perots, or lamellar • ~10^{-16} W/$\sqrt{Hz}$ NEP • Large dimensions with $\lambda/\lambda\Delta = 10^5$ • Single detector option
3. 40 X 40 stressed Ge:Ga imager	100-200 μm	• ~10^{-16} W/$\sqrt{Hz}$ NEP
4. 10 X 10 bolometer imager	200-1000 μm	• ~10^{-16} W/$\sqrt{Hz}$ NEP • A backup for the 100-200 μm range
5. 10 X 10 Fourier transform spectrometer	~10-1000 μm	• 1 m travel, folded optics • Large pixels for 40 arcsec coverage • Bolometer array • Heterodyne instead? • ~1 m^3 estimated volume
6. Heterodyne package	110-652 μm	• ~500 W required for carcinotron(s) • Common back-end • ~2 m^3 estimated volume
a. 522-652 μm		• NH_3, CO, H_2O, C, . . . • 5 times quantum noise limit
b. 361-455 μm		CO, NH, . . .
c. 110-157 μm		Narrow band for selected lines: CII? HD?
7. 40 X 40 Si:In imager or ~2 X 100 spectrometer	1-4 μm	• ~3/4 mm pixels (large) • 2 gratings/2 arrays • ~5 X 10^{-17} W/$\sqrt{Hz}$ NEP

TABLE III-6.– COMMENTS ON PRESENT LDR REPRESENTATIVE SYSTEM CONFIGURATION

Characteristic	Comment
1. 1.5 kW allowed for instruments*	Estimate ~6 kW, without communication electronics needs
2. Instruments' volume*	One-half of Shuttle bay?
3. Modularity of instruments	Probably harder than Space Telescope
4. Date rate	About Space Telescope rate
5. 3 arcmin FOV, 20 m diameter	Large but plausable dimensions for instrument components
6. Equitorial orbit	Stability problems? FTS would like 20-min integration times
7. Disturbing torques	Should be minor • Estimate 10^{-3} to 10^{-2} N-m from cooler • ~10 kg moving 1/2 m in 20 min for FTS

IV. CONCLUSIONS

A. HIGHLIGHTS OF LDR SCIENCE

Viewed in the broadest sense, the scientific rationale for LDR imposes two crucial instrumental requirements: angular resolution approaching 1 arcsec in the 100-μm wavelength region and high-resolving-power spectroscopy with good sensitivity. This reflects the historical experience in the optical and radio wavelength bands in which imaging and spectroscopic capabilities brought a new dimension to our understanding of the universe. These two themes recur throughout the range of scientific problems discussed at this workshop.

LDR, with angular resolution of 1 arcsec, will bring into much sharper focus our view of the universe at IR wavelengths. This resolution will allow us to resolve and study in detail a number of objects ranging from distant galaxies to spiral arms in distant galaxies, to giant molecular clouds (GMC) in nearby galaxies, to the collapsing precursors of protostars in our own galaxy, and, perhaps, to planetary systems around nearby stars and to the bands and the Great Red Spot on Jupiter.

The second major theme for LDR will be sensitive observations of spectral lines. The region from 1 to 1000 μm is crowded with spectral lines of important molecules, atoms, and ions. These lines can be used to probe the physical, chemical, and dynamical conditions in objects as diverse as giant molecular clouds in external galaxies and comets within our own solar system. The critical role for LDR in this area arises from its large collecting area, which allows the detection of very weak lines in small ($\lesssim$1 arcsec) sources, and from its ability to accommodate the complex instrumentation required for spectroscopic observations.

LDR is essential for investigating a wide range of scientific problems detailed in Volume II of this report. The two areas in which LDR will have the greatest effect, as anticipated by the Astronomy Survey Committee, are in studies of the formation of stars and planetary systems and in studies of the structure of the early universe.

1. Major Telescope Requirements Derived from Science Rationale

The major conclusions of the Asilomar Science Workshop concerning the telescope requirements derived from scientific rationale are summarized as follows. It was agreed that, since much of the astronomy anticipated is spectroscopic, the telescope need not be at temperatures less than 150 to 200 K. Such temperatures are achievable by passive cooling and a thermal shield. The angular resolution required to provide a major step in our understanding of star formation is about 1 arcsec. For 100 μm, characteristic of emission from star forming regions, this implies a telescope of approximately 20-m diameter.

The reflecting surface should be sufficiently accurate to provide diffraction-limited performance to about 30 to 50 μm. As a secondary goal, it may be desirable to have the capability for making observations in a light-bucket mode in the 1- to 4-μm range, with a blur circle of about 1 to 2 arcsec. Such capability would give LDR unprecedented power in detecting distant galaxies, determining the overall structure of the universe, and predicting its ultimate fate.

B. GENERAL DESCRIPTION OF LDR

One goal of the Asilomar conference was to begin to define the physical parameters of LDR which would be required to achieve the currently anticipated astronomical objectives. As currently conceived, LDR is an approximately 20-m-diameter reflecting telescope deployed in space with a single Shuttle launch. Presently, we envision a free-flying observatory. However, it may be attached to a proposed Space Platform, and it may eventually involve several Shuttle launches and include multiple components. It will be operated as a major national observatory with a lifetime of 10 or more years. Revisits may occur more frequently to replenish cryogens and change instruments.

The physical configuration of LDR is not yet certain, and the project poses many intriguing technical challenges. There are some obvious factors to take into account. The weight and volume constraints of the Shuttle (particularly to polar orbits), the demands of the space environment, and the projected status of technology available for LDR limit the range of options available. Preliminary technical studies have defined the following general characteristics which any design for LDR must have:

1. Because of the limited size of the Shuttle bay, which is 4-m wide, a larger LDR cannot be carried into orbit as a unit. Instead, the reflector surface may have to be built from smaller mirror segments, less than 4 m in diameter. These segments and their associated backup truss must be deployed or assembled in space to form the finished telescope. One alternative to this might be a 4- by 18-m rectangular reflector.

2. The segments themselves must be of low areal density (mass/m^2 of reflector) because of the limited carrying capability of the Shuttle. For a 20-m-diameter LDR, the maximum allowable areal density of the reflecting surface is about 22 kg/m^2. This is considerably lower than the areal density of conventional optical telescopes (for comparison, the ST mirror has an areal density of approximately 180 kg/m^2), although glass segments of areal density $\ll$100 kg/m^2 have been fabricated. By contrast, precision high-frequency radio telescopes now operating at submm wavelengths longward of approximately 300 μm have areal densities as low as 20 kg/m^2. A lightweight mirror segment capable of meeting the LDR requirement of a 30-μm diffraction limit has not yet been built, and finding a suitable segment material is a major technological challenge to the project.

3. Both the expected imprecision of the deployment process and the response of the segmented surface to the varying thermal and mechanical disturbances during its orbit require that the relative positions of the segments be controlled; some form of "active optics" will be required to maintain acceptable image quality. This requires a means of sensing the positions of the segments (or the quality of the image) and a means of moving the segments to achieve the desired figure. It is not anticipated, however, that the figure of each individual panel will have to be controlled.

4. LDR should be thermally stable to minimize corrections to the surface figure and to prevent degraded performance in the sensitive IR detectors. For these reasons, LDR must be provided with a thermal shield to protect the surface from direct sunlight; limits on how closely the line of sight can approach the Sun will also be necessary.

In summary, LDR is conceived as a telescope with a segmented, actively controlled primary reflector which is fabricated of extremely lightweight materials. A thermal shade will be required for thermal protection of the system. The telescope will possibly be carried into space in a single Shuttle launch and be deployed or assembled in space before being placed in its final orbit. Atmospheric drag on the large surface area will require an orbital altitude of ~700 km instead of the normal ~300 km operating limit of the Shuttle, so that an additional propulsion unit will be part of the package.

These preliminary considerations were combined with the astronomical and technical considerations at the workshop to produce a set of performance requirements and representative system parameters. These appear in table IV-1; an artist's conception of what such a telescope might look like is shown in figure I-1.

Because the main scientific payoff from LDR will result from observations at high spectral and spatial resolving power, emphasis will be placed on instruments to achieve good resolution. For the highest spectral resolution, coherent detection with heterodyne techniques similar to those of radio astronomy can be used at submm wavelengths. Spectral resolving power ($R = \nu/\delta\nu = \lambda/\delta\lambda$, where ν is the frequency, $\delta\nu$ or $\delta\lambda$ is the resolution, and λ is the wavelength) in excess of 10^6 can be achieved with these techniques, at least to wavelengths as short as 100 to 200 μm. For shorter wavelengths and/or lower spectral resolving power (perhaps in the range R = 100 to $R = 10^4$–10^5), spectrometers of various types – grating instruments and Fabry-Perot and Michelson interferometers – will probably be used. The detectors to be used with these spectrometers would include both IR-sensitive, photoconductive devices and bolometers, the latter being used at the longer wavelengths ($\gtrsim$200 μm). Both single- and multielement (array) detectors will be used with the spectrometers.

TABLE IV-1.– LDR SYSTEM PARAMETERS AND PERFORMANCE REQUIREMENTS

Parameters	Requirements
Diameter	20 m primary, 1 m secondary
Field of view	$\geqslant$3 arcmin
F/Ratio	System F/10, primary F/0.5
Shortest wavelength of diffraction-limited performance	30-50 μm (aperture efficiency > 30% at 30 μm)
Light-bucket blur circle[a]	2.0 arcsec (at 1–4 μm)
Optics temperature	Primary $\leqslant$200 K ($\pm$1 K uniformity), secondary $\lesssim$125 K ($\pm$1 K uniformity)
Emissivity (system)	0.05
Absolute pointing	0.05 arcsec
Jitter	0.02 arcsec – within 1 min after slew
Slew	$\gtrsim$50°/min
Scan	1° X 1° – linear scan at 1°/min
Track	0.2°/hr (for comets $\gtrsim$25° from Sun)
Orbit requirements[b]	750 km altitude
Chopping	Yes, 2 Hz, 1 arcmin (reactionless)
Sidelobes	Low near sidelobes
Other	Limited cross polarization
Thermal shade L/D	1
Sky exclusion	$\gtrsim$90° Sun from Sun, $\gtrsim$45° from Earth
Cryo system	Various temperatures in the range 0.1 K to 50 K, 1.5 kW total power required
Lifetime	>10 yr, approximately 3 yr revisit
Deployment mode	Person(s) assisted (if necessary)
Mass	27,000 kg total (one shuttle)
Weight of instruments	3000 kg (including cryogen)

[a]The tolerances (e.g., rms surface accuracy) needed to achieve a value of 2 arcsec for the light-bucket mode are more severe than the tolerances associated with a diffraction limit of 50 μm. This requirement will be studied further.

[b]Polar orbit desirable but may require multiple shuttle flights. Particle radiation may cause consideration of a lower orbit.

Broadband photometric and mapping observations can be carried out with a variety of instruments based on detectors similar to those described above. We can anticipate, however, that in the LDR era monolithic IR arrays will be in wide use. An array can be incorporated with a suitable optical system into an IR camera which will provide images at IR wavelengths and utilize the spatial resolving power of LDR.

A range of filters permitting observations of narrow spectral features will be incorporated into such a camera; additionally, the camera could be used in tandem with a spectrometer for true spectral imaging. Polarizers could be added to the system so that polarization measurements could be made. For certain types of specialized measurements (e.g., high-time resolution studies), a single detector optimized for a particular purpose may be preferable to an array. We can anticipate that most instruments will require some form of cooling to temperatures from 0.1 to 50 K for satisfactory operation, so that cryogenic systems will accompany the telescope and instruments into space.

C. COMPARISON OF LDR WITH OTHER TELESCOPES

1. Current and Future Infrared and Submillimeter Telescopes

A 20-m-diameter LDR would provide approximately 20 times better spatial resolution and 400 times more collecting area than the 1-m class airborne and balloon-borne telescopes now in use at wavelengths between 30 and 600 μm. The increased aperture leads to a dramatic jump in scientific capability and makes possible the exciting and important investigations described herein.

At some wavelengths between 300 μm and 1 mm, it is sometimes possible, though difficult, to observe from mountaintop sites; large ($\gtrsim$10 m) ground-based telescopes for this purpose will certainly come into use before LDR is launched. Like the airborne and balloon-borne telescopes, these ground-based telescopes will be important scientific and technical precursors of LDR; however, the atmospheric windows in the 300-μm to 1-mm range are narrow and variable. For most purposes, the total freedom from atmospheric effects should make LDR much more powerful than a comparably sized ground-based telescope, which, in any case, could not operate in the LDR primary range of 30 to 300 μm. Similarly, if LDR can be used in the light-bucket mode at $\lambda \lesssim 4$ μm, LDR will be much more sensitive in the near-IR than even the 10- to 20-m diameter New Technology Telescopes projected for the next generation. This is a result of lower LDR temperature and the absence of atmospheric attenuation and emission.

LDR will also complement other space telescopes planned for IR observations over the coming decade. Comparison of LDR with the Cosmic Background Experiment (COBE), the Infrared Astronomical Satellite (IRAS), and the Shuttle Infrared Telescope Facility (SIRTF) – each cryogenically cooled and, therefore, very sensitive – is particularly instructive. COBE is designed explicitly to study the diffuse cosmic background radiation. Its three instruments span the wavelength range from 1 μm to 1 cm. The highest angular resolution achievable from COBE will be 1°; its findings will thus be complemented by the higher angular resolution provided by LDR. These fine-scale measurements are crucial for investigating small-scale signals from the galaxy-formation epoch. IRAS (size ~0.6 m) has surveyed the sky at IR wavelengths to very low flux levels and cataloged tens of thousands of previously unknown sources, many of which will be seen primarily with a spatial resolution of approximately 100 arcsec at 60 and 120 μm, wavelengths where LDR will be very powerful. IRAS has no spectroscopic capabilities for wavelengths longer than about 30 μm. Because of its much larger aperture and spectroscopic capabilities, LDR will be sensitive enough to study many IRAS sources in great detail and will give us our first information on the sizes and structures of the sources on scales $\lesssim$30 arcsec. SIRTF (size ~1 m) will be an observatory-class facility with interchangeable focal-plane instruments. It is designed to operate from 1.8 to 700 μm, and its very cold ($\lesssim$7 K) optics will make it 100 to 1000 times more sensitive than presently existing IR instrumentation from 5 to 200 μm.

SIRTF will therefore open many new fields for study and exploration in the IR. LDR is designed to be especially effective in the submm ($\lambda \gtrsim 200\ \mu m$), where telescope cooling is not so important, and possibly also at 1 to 4 μm, short of its own emission peak. The spatial resolution of LDR will be greater than that of SIRTF. LDR will also be more sensitive for many spectroscopic observations because the temperature of the optics matters little at high spectral-resolving power.

The scientific complementarity of LDR, SIRTF, and other facilities is shown in figure IV-1, in which spectral resolving power is plotted versus wavelength. The characteristic spectral resolution and wavelength used to study a number of key scientific problems are shown, as is the domain in which each telescope system can be used most advantageously. Although the demarcation is not sharp and distinct, it is shown that LDR will certainly be the instrument of choice for high-spectral-resolution observations at wavelengths >>30 m and for most measurements at wavelengths between 200 μm and 1 mm, whereas SIRTF will be used most effectively for low to moderate spectral resolution at wavelengths from –3 to 200 μm. Large ground-based telescopes can be used for high-spectral-resolution work at wavelengths shortward of 30 μm and may achieve higher sensitivity than SIRTF for most measurements at wavelengths <3 μm. If a light-bucket mode is implemented, LDR may also be very powerful for selected problems at wavelengths of <30 μm. An important dimension not displayed in the figure is that of spatial resolution and FOV. At any wavelength in which it is diffraction-limited, LDR will achieve substantially higher spatial resolution than SIRTF. On the other hand, for observations of spatially extended objects SIRTF's cryogenic optics give it advantages over LDR beyond those shown in figure IV-1.

At wavelengths longer than 100 μm, large, ground-based, millimeter-wavelength telescopes such as the 30-m IRAM (Institut de Radio Astronomie Millimetrique) telescope will excel, although atmospheric transparency makes the exact boundary here uncertain. The ST will have unexcelled capabilities for observations from 1 μm shortward to the ultraviolet.

2. Facilities for Use at Other Wavelengths

LDR, as the first major facility for far-IR and submm wavelengths, is comparable in magnitude and scientific importance to current and planned major facilities being developed for use in other spectral bands. Scientifically, LDR complements ST, AXAF, and large ground-based radio and optical telescopes.

LDR will provide far-IR images of galaxies with angular resolution comparable to that obtained in visual photographs from the ground. Similarly, LDR will explore regions of star formation mapped with comparable angular resolution in lines of CO and NH_3 by advanced millimeter-wave interferometers and by the Very Large Array (VLA) radio telescope, LDR studies these regions at the wavelengths in which they emit most of their energy and will therefore have many magnitudes more sensitivity than the millimeter instruments – enough to detect advanced stages of star formation and the formation of planetary systems.

As a mature observatory, LDR will not just complement telescopes that operate at neighboring wavelengths. For instance, LDR studies of the Sunyaev-Zeldovich effect in clusters of galaxies will be combined with X-ray observations from AXAF to determine Hubble's constant.

Facilities like LDR, ST, AXAF, and the VLA bring immense increases in capability to their respective disciplines. The recent history of astrophysical exploration shows that such leaps in instrumental capability lead to the solution of pressing astrophysical problems and to the discovery of entirely new phenomena.

LDR will bring major advances in performance for high spatial and spectral resolution work across almost three decades of wavelength from 2 to 1000 μm. Together, these advanced facilities will attack astrophysical problems across the entire frontier. LDR, with its unique capabilities for studying cosmology and

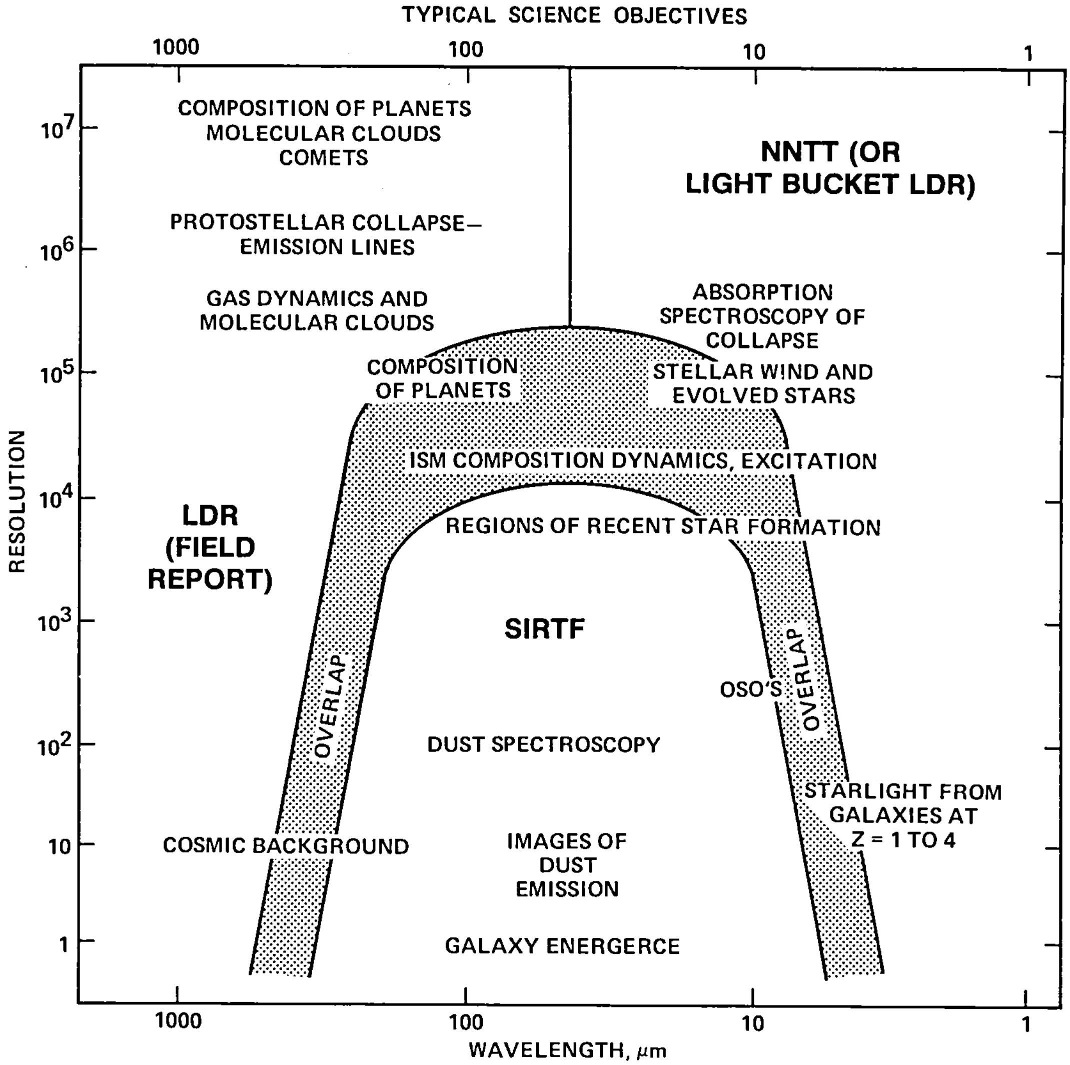

Figure IV-1.– Complementarity of LDR, SIRTF, and other facilities.

star formation, will play a crucial role in these investigations and will become one of our major resources for astronomical research for decades.

D. CLOSING TECHNICAL REMARKS

In general, it was found that some areas of LDR are within the state of the art and others will be achieved in the near-term by NASA or military-sponsored developments. However, there are many unique areas in all the major technology disciplines that will have to be specifically funded for LDR. If the guideline for an LDR phase C/D start in the late 1980s is to be met, an intensive LDR technology program of 3- to 5-yr duration must be started soon and will require millions to tens of millions of dollars of funding per year. The feasibility of a late 1980s LDR phase C/D start would be dependent on the success of such an intensive LDR technology program.

It was the concensus of the Workshop Technology participants that there was moderate to high risk in such a technology program providing a sound basis for a late 1980s LDR phase C/D start and an absolute

certainty that such dates could not be made without significant technology effort being funded in the next several years. Again, it should be emphasized that the Workshop Technology Panels achieved only a first step in defining the technology issues. The many recommendations of the Technology Panels all require further investigation.

The existing LDR technology development plan (updated Nov. 1981) needs to be updated again based upon these recommendations. Further systems definition studies and mission/telescope/technology tradeoffs are required, such as orbit versus weight versus sunshade/thermal control, and light bucket versus diffraction-limit. A Phase A study in the near-term is essential for providing guidance for an LDR technology program.

Finally, workshops such as this one, on an annual basis, would be extremely useful to reexamine technology versus performance requirements in a technology field that is rapidly evolving.

APPENDIX A

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APPENDIX B

GLOSSARY

angular resolution
The minimum angular separation of two point sources that the telescope could resolve; the angular size of the blurred image of a point source.

carcinotron
A backward wave oscillator that is a source of approximately monochromatic radiation.

diffraction-limited
The angular resolution is limited by the diameter D of the telescope and is proportional to λ/D, where λ is the wavelength. This means that the mirror surface is, for practical purposes, perfect and no amount of polishing, etc., will improve the angular resolution.

light-bucket blur circle
The angular size of the blurred image of a point source observed in the light-bucket regime. Usually defined so that, for example, 50% of the light falls into this angular cone.

light-bucket operation regime
The regime in which the angular resolution or the light-bucket blur circle depends not on the diameter of the mirror, but on the quality of the mirror surface, alignment of the mirror, etc. (also referred to as the geometric optics regime).

spatial resolution
The same as angular resolution, but translated to a length and therefore dependent on the distance of the source or sources from the telescope; for example, 1-arcsec angular resolution means 92 million miles spatial resolution at a distance of 3 ℓ.y., but 184 million miles spatial resolution at a distance of 6 ℓ.y.

APPENDIX C

ABBREVIATIONS AND ACRONYMS

ARC	Ames Research Center
AU	astronomical unit
AXAF	Advanced X-Ray Astrophysics Facility
B/G	background
BASD	Ball Aerospace Systems Division
CBR	cosmic background radiation
CCD	charge-coupled device
CIT	California Institute of Technology
CMG	control momentum gyroscope
COBE	cosmic background experiment
c.t.e.	coefficient of thermal expansion
DARPA	Defense Advanced Research Projects Agency
EMI	electromagnetic interference
ESTEC	European Space Technology Center
FOV	field of view
FTS	Fourier Transform Spectrometer
GMC	giant molecular cloud
HAC	Hughes Aircraft Company
HCO	Harvard College Observatory
HPBW	half-power bandwidth
HQ	headquarters
IF	intermediate frequency
IFOV	instrument FOV
IR	infrared radiation
IRAM	Institut de Radio Astronomie Millimetrique
IRAS	Infrared Astronomical Satellite
JPL	Jet Propulsion Laboratory
KAO	Kuiper Airborne Observatory
KPNO	Kitt Peak National Observatory
L/D	length/diameter ratio
LaRC	Langley Research Center
LDR	Large Deployable Reflector
LMSC	Lockheed Missiles and Space Company, Inc.
LOS	line of sight
ℓ.y.	light year(s)
MIT	Massachusetts Institute of Technology
MMC	Martin-Marietta Corporation
MSFC	Marshall Space Flight Center
N/A	not applicable
NASA	National Aeronautics and Space Administration
NEP	noise equivalent power
NRAO	National Radio Astronomy Observatory
NRL	Naval Research Laboratories
OAST	Office of Aeronautics and Space Technology
OSSA	Office of Space Science and Applications

PE	Perkin-Elmer Corporation
RADC	Rome Air Development Center
RI	Rockwell International
SAO	Smithsonian Astrophysical Observatory
SBRC	Santa Barbara Research Center
SIRTF	Shuttle Infrared Telescope Facility
SIS	superconductor-insulator-superconductor
SPIE	International Society for Optical Engineering (formerly the Society of Photo Optical Instrumentation Engineers)
ST	Space Telescope
STS	space transportation system
SUNY	State University of New York
submm	submillimeter
TBD	to be determined
TRW	TRW, Inc.
UCB	University of California at Berkeley
UCLA	University of California at Los Angeles
ULE	ultra-low-expansion
VLA	Very Large Array

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16. Abstract

The Science and Technology Workshop on the Large Deployable Reflector (LDR) convened on June 21–25, 1982, to discuss a large ambient-temperature, far-infrared/submillimeter telescope in space. This document summarizes the results of the scientific and technical activities at the Workshop. The scientific effort consisted of reviewing the science rationale for LDR and arriving at a concensus set of scientific requirements. The technologists then took these scientific requirements and developed telescope requirements. These telescope requirements were then compared to the current and anticipated state of the various technologies involved, and technological shortfalls were identified.

The results of the Workshop consisted of a set of science and technology requirements for LDR; several recommendations were made. A large-system study of LDR was recommended to better define the concept. Continued scientific involvement in the technology development was also recommended. It was the consensus of the technology group that the technology to implement LDR did not currently exist and that without augmentation to the ongoing technology programs that LDR could not be successfully started in the early 1990s. A technology development program to augment the current technology programs was recommended.

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